Band 20 _ PRODUKTION UND ENERGIE

Rebekka Volk

PROACTIVE-REACTIVE, ROBUST SCHEDULING AND CAPACITY PLANNING OF DECONSTRUCTION PROJECTS UNDER UNCERTAINTY

KIT Scientific Publishing

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Proactive-reactive, robust scheduling and capacity planning of deconstruction projects under uncertainty

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Kurzfassung

Die Dissertation umfasst die Entwicklung eines Projektplanungs- und Entscheidungsunterstützungssystems für die robuste Zeit- und Kapazitätsplanung von Projekten und dessen Anwendung in zwei Fallstudien zum Rückbau von Bauwerken.

Für die Planung von Projekten im Gebäuderückbau stehen oft keine vollständigen Informationen zur Verfügung, da Gebäude in ihren langen Nutzungsdauern verändert werden und die Veränderungen häufig nur teilweise dokumentiert werden. Wenn ein Gebäude nicht mehr genutzt werden kann, erfolgt die Planung des Gebäuderückbaus anhand von Ausschreibungsunterlagen, Gebäudedokumentationen und Gebäudebegehungen. Aus Zeit- und Kostengründung erfolgt jedoch meist keine umfassende Gebäudeauditierung und -erkundung. Im Fall der Projektplanung unter Unsicherheit im Gebäuderückbau wirken sich jedoch bestimmte Unsicherheiten unterschiedlich stark auf die Projekt- und Ressourcenplanung aus, die in der Planung berücksichtigt werden müssen. Im Rahmen dessen fallen verschiedene operative Entscheidungsprobleme an (z.B. Modeauswahl oder Ressourcenallokation), in denen die Herausforderung in der adäquaten Berücksichtigung des Systemzustands der Umwelt (Gebäude) liegt. Entscheidungsträger sind zudem an robuster und risikoneutraler/-averser Planung interessiert, die vorhandene Risiken quantifizieren und berücksichtigen kann. Unzureichende oder nicht verfügbare Informationen bezüglich des Systemzustands bedingen aus entscheidungstheoretischer Sicht eine Situation unter Ungewissheit. Zusätzlich kann sich der Systemzustand aufgrund dynamischer Entwicklungen über die Zeit ändern, beispielsweise ausgelöst durch Veränderungen der Ressourcenverfügbarkeit oder der realisierten Aktivitätsdauern.

Der in der Dissertation entwickelte Ansatz unterstützt Entscheidungsträger bei der Projekt- und Ressourcenplanung unter Berücksichtigung von Unsicherheiten in Rückbauprojekten mit dem Ziel der robusten Projektplanung. Das Modell generiert proaktiv Szenarien, für die jeweils ein zeitoptimaler Projektzeitplan und eine Projektstrategie (Sequenz von Aktivitäten) für multimodale Aktivitäten unter beschränkten Ressourcen und Einsatzorten berechnet werden. Mithilfe eines Optimiermodells wird die analytische Lösung des Entscheidungsproblems ermittelt. Die generierten, alternativen Projektstrategien werden dann mittels einer Heuristik auf alle Szenarien angewendet und verschiedene Robustheitsmaße werden berechnet. Basierend darauf werden dem Entscheidungsträger optimalitätsrobuste Lösungen basierend auf Regret-Werten vorgeschlagen, die unter allen Szenarien hinsichtlich Projektdauer und Projektkosten am besten abschneiden und die Eignung der Alternativen einschränken. Dabei kann die Risikopräferenz des Entscheidungsträgers berücksichtigt werden. Für den Fall dynamischer Entwicklungen der Projektumwelt (Ressourcenverfügbarkeit, realisierte Aktivitätsdauern etc.) werden alternative, reaktive Suchstrategien vorgeschlagen. Das entwickelte Modell wird in zwei Fallstudien angewendet. Diese adressieren Entscheidungssituationen der Rückbau-Projektplanung im Wohngebäude- und Nicht-Wohngebäudebereich.

Abstract

In this research, a project planning and decision support model is developed and applied for deconstruction projects to identify and reduce risk and uncertainty in deconstruction project planning.

To support decision makers in deconstruction project planning, a proactive scenario construction is developed that considers three main uncertainties in deconstruction projects. For each scenario, a time-optimal project plan (schedule) and deconstruction strategy (sequence) is calculated with multi-modes, and constrained resources and locations onsite (MRCPSP). The generated deconstruction strategies are then reapplied onto all scenarios by a list scheduling heuristic and the most optimality-robust deconstruction strategy is identified and recommended to the decision maker. Here, for risk-neutral decision makers the optimality-robust strategy is identified by the minimum average absolute regret of the objective value. Also, a reactive and flexible model element is proposed that can be applied in the case of schedule infeasibility during project execution. This allows decision makers to decide on local searching or rescheduling procedures to find a nearly as robust solution in the set of identified deconstruction strategies or a new robust deconstruction strategy for the remainder of the project.

To plan projects, methods of operations research are applied to schedule project activities and resources and to confine project plans to time and resource constraints. In deconstruction project planning theory, project planning under certainty or fuzziness are used for that purpose. However, this contribution allows calculating and comparing different scenarios for different project framework conditions and it recommends robust decisions and project plans to decision makers according to their risk attitude.

Furthermore, locations are explicitly modeled as a renewable resource in deconstruction project planning which helps to avoid working team jamming and to improve onsite logistics of machinery, deconstructed material and deconstruction building elements and material masses.

In two case studies comprising a residential and a non-residential building, the applicability of the developed model is shown, the decision making support is demonstrated and the model results are verified with literature and measured real data. As the decision making based on risk attitudes is associated with the subjective uncertainty perception and risk assessment, sensitivity analyses are performed to examine their influence on model results and decision recommendations.

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Abbreviations

AR	Absolute regret value
BaustellV	Verordnung über Sicherheit und Gesundheitsschutz auf Baustellen
BGVR	Berufsgenossenschaftliches Vorschriften- und Regelwerk
BGL	Baugeräteliste
BIM	Building Information Model(s)/Modelling (defined in ISO 29481-1:2010(E))
BKI	Baukosteninformationszentrum Deutscher Architekten-kammern GmbH (http://www.baukosten.de/)
BRTV	Bundesrahmentarifvertrag für das Baugewerbe vom 4.07.2002 zuletzt angepasst am 10.12.2014
CPM	Critical Path Method
CSV	Comma-separated values (open data format for simple text files)
DAfStb	Deutscher Ausschuss für Stahlbeton
DDT	Dichlorodiphenyltrichloroethane
eANV	Elektronisches Abfallnachweisverfahren (German electronic waste tracking system)
EDD	Earliest due date
EPD	Environmental product declaration
ERP	Enterprise resource planning
EVPI	Expected value of perfect information
EWC	European Waste Catalogue and Hazardous Waste List
GAN	General Activity Networks
GERT	Graphical Evaluation and Review Technique
GFA	Gross floor area
GISBAU	Gefahrstoff-Informations-System Bau
GV	Gross volume (defined in DIN 277:2005-02, §3.2)
HBIM	Historic building information models

IFC	Industry Foundation Classes (ISO/PAS 16739:2005)
LBS	Location Breakdown Structure
LC	Life cycle
LCA	Life Cycle Assessment
L(E)PT	Longest (expected) processing time
LoD	Level of Detail
LTB	Liste der technischen Baubestimmungen
MFH	Multifamily house
MPM	Metra Potential Method
MRCPSP	Multi-Mode Resource-Constrained Project Scheduling Problem
NPV	Net present value
OBJ	Open data format for 3D objects (ASCII format)
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyl
PCP	Pentachlorophenol
PERT	Program Evaluation and Review Technique
RA	Residential accommodation (Wohnheime)
RC	Recycling
RCPSP	Resource-constrained project scheduling problem
REFA	Association for work design, industrial organization and business development (Verband für Arbeitsgestaltung, Betriebsorganisation und Unternehmensentwicklung)
RF	Resource factor
RFID	Radio frequency identification
RS	Resource strength
RT	Restrictiveness
SFH	Single family house
STLB-Bau	List of standard construction services (Standardleistungsbuch Bau)
TEQ	Technical equipment
TRGS	Technical guidelines for hazardous materials (Technische Regeln Gefahrstoffe)
VSS	Value of the stochastic solution
WBS	Work Breakdown Structure
WDVS	Thermal insulation composite system (Wärmedämmverbundsystem)
(W)S(E)PT	(Weighted) shortest (expected) processing time

Symbols

Symbols of the building inventory calculation (part A)

e	Building element types inherent in deconstruction building, $e \in E$
e'	Building elements inherent in deconstruction building, $e' \in E'$
$\tilde{e}_{e'}$	Opening building element that is enclosed by building element e', $\tilde{E} \subseteq E'$
δ_e	Building element thickness
$A_{e,f}$	Building element surface of facial building element f
$V_{e,f}$	Building element volume
$M_{e,f}$	Building element mass
$V_{e'}$	Volumes of building element e'
Y_e	Materials of building element type e
DC_e	Duration coefficients of building element type e
h_e	Building element height
l_e	Building element length
w_e	Building element width
$\varepsilon_{wall,=}$	Correction factor in the volume calculation of walls with the same (=) thickness
$\varepsilon_{wall,\Delta}$	Correction factor in the volume calculation of walls with the differing (Δ) thicknesses
$\varepsilon_{ceil./floor}$	Correction factor in the volume calculation of ceilings and floors
$\rho_{e,y}$	Material density of building element e and material y
GFA	Gross floor area excluding the foot area of the exterior walls
GFA_{ext}	Gross floor area including the foot area of the exterior walls
GV	Gross volume excluding the volume of the exterior walls
GV_{ext}	Gross volume including the volume of the exterior walls

Symbols of the scenario construction (part A)

k	Scenarios, represented by a vector of building elements e‘ and their durations $d_{j(e')m}$
z_{ks}	Scenario z is a set of potential realizations in s stages that induce a specific set of activity durations d_{jmst} depending from scenario number k and stage s
s	Stages $s = 1, \dots S$ as flexible decision points in time where information update come up or activities have to be scheduled
t	Time $t = 1, \dots \bar{T}_J$ (minutes, hours or days), with $\bar{T}_J$ as upper bound/deadline of project makespan
$\xi_{s,t}$	Observation matrix of project status at stage s and time t
x^k	$= (x_1^k, \dots, x_S^k)$; decision sequence of all stages s for scenario k

Symbols of the scheduling problem (part B)

x_{jmst}	Binary decision variable defining the schedule (starting or finishing times of activities). Here x is defined as finishing times of activities in their applied modes with: $x_{jmst} = \begin{cases} 1, if\ activity\ j\ in\ mode\ m\ is\ finished\ in \\ \quad period\ t\ and\ in\ stage\ s \\ 0, else \end{cases}$
j	Activity sets $j = 1, \dots J$; with $j \in \{1, J\}$ as dummy source and sink activity sets representing start and end of the project with resource demand $q_{j=1,m}^r = q_{j=J,m}^r = 0$;
$\lvert J \rvert$	Cardinality of J represents the number of activities j
i	Preceding activity sets of activity set j, $i \in P_j$ where P_j describes all predecessor activity sets of activity set j
$C_{max,UB}$	Upper bound of project makespan
m	Mode $m = 1, \dots M_j$ of activity j, with M_j as the set of possible modes of activity set j
d_{jm}	Activity set duration (processing time); $E(d_{jm})$ is the expected duration of activity set j in mode m; $d_{1m} = E(d_{1m}) = p_{Jm} = E(d_{Jm}) = 0$

P_j / S_j	Set of direct predecessors / successors of activity set j. This is depicted either by the activity-on-node or activity-on-arc network or the precedence matrix.
N_j	$= \{1, \dots, J\} \backslash (P_j \cup S_j)$ denotes the sets of activities which can run in parallel with j
ES_j , LS_j	Earliest (release) resp. latest starting times of activity sets j; $ES_1 = LS_1 = 0$; $LS_J = \bar{T}_J - d_{Jm} = \bar{T}_J$
EF_j , LF_j	Earliest resp. latest (deadline /due dates) finishing times of activity set j; $EF_1 = LF_1 = 0$; $LF_J = \bar{T}_J$
r	Renewable resources $r = 1, \dots, R$ (e.g. machines, staff)
l	Renewable locations $l = 1, \dots, L$ (e.g. locations, rooms or floors in a building according to location-breakdown structure)
n	Non-renewable resources $n = 1, \dots, N$ (e.g. budget)
q_{jm}^{r}	Required resources of activity j in mode m for renewable resource r in period t with Q_r as amount of per period availability of resource r, with $1 \leq t \leq T_J$
q_{jm}^{l}	Required locations of activity set j in mode m for location l in period t with Q_l as amount of per period availability of location l, with $1 \leq t \leq T_J$
q_{jm}^{n}	Required resources of activity set j in mode m for non-renewable resource r in period t with Q_n as amount of availability of resource r over project makespan T_J
Q_r^{min}, Q_r^{max}	Lower and upper bounds for resource capacity of renewable resource R
T_J, C_{max}	Project makespan
$\bar{T}_j$	Deadlines or due dates of activities $j \in J$. The project deadline is depicted by $\overline{T_J}$ of the last (dummy) activity of the project.
RF	Resource factor
RS	Resource strength
RT	Restrictiveness

Symbols of the cost estimation (part B)

C_{total}	Total project cost [EUR]
C_{fix}	Fixed project cost [EUR]
$C_{var,j'}$	Variable cost of activity j' [EUR]
RV_r	Replacement value of resource r [EUR]
SL_r	Expected service life time of resource r [years]
SC_r	Supply cost of resource r [EUR]
IC_r	Interest rate of resource r [EUR]
$U_{e'}$	Units of building element e' that are deconstructed in activity j' [m³, m², m, piece]
v_m	Velocity of the assigned mode m per building element unit [h/m³, h/m², h/m, h/piece]
$c_{U(e')}$	Cost factor for building element e', depending on units of building element e' [EUR/h]
$c_{e'mr}$	Cost factor for building element e', depending on units of building element e', building mode m and resource r [EUR/h]
$c_{ind,J}$	Cost factor for indirect project cost dependent on project makespan T_J [EUR/h]
C_{other}	Other project cost [EUR]

Symbols of the evaluation of robust deconstruction strategies (part C)

$Sched^*(z_k)$	Optimum schedule of the MRCPSP of scenario z_k
$\Pi^*(z_k)$	Resulting 'best' deconstruction strategy in scenario z_k from $Sched^*(z_k)$
$\Pi^*(Z)$	'Best' deconstruction strategy in all scenarios (robust strategy)
$Seq(j,R,L)$ $Seq(j,r)$	Sequence of scheduled activities j on resources R and locations L also described as precedence: $j_\alpha \prec j_\beta, \forall j_\alpha, j_\beta \in J, \forall r \in R$
$C_{max}^{\Pi^*(Z)}$	Project makespan of 'best' deconstruction strategy $\Pi^*(Z)$
$AR(\Pi(Z))$	Absolute regret value of 'best' strategy in all scenarios Z

Symbols of the information update and project strategy/ schedule change (part D)

$\phi_{st}(\Pi^*(Z))$	Set of remaining activities to be scheduled at time t and stage s
$x_{jmst}^{\phi} \in \phi$	Remaining decisions (activities) to be made (scheduled) at time t and stage s
$\varphi_{st}(\Pi^*(Z))$	Set of completed activities at time t and stage s
$x_{jmst}^{\varphi} \in \varphi$	Scheduled and realized decisions (activities) at time t and stage s

1 Introduction

1.1 Current situation and set of problems[1]

Current situation

In Germany, about 18.4 million residential buildings (Statistische Ämter des Bundes und der Länder 2013) and 2.5 million non-residential buildings (Dirlich et al. 2011; Gruhler and Böhm 2011; Kohler et al. 1999) account for the German building stock. In recent studies, the German building stock was classified into building types according to their type of use, their year of construction and their energetic quality characteristics (IWU 2005, 2011, 2012a). Change and consolidation processes in metropolitan areas, standards of resource preservation or obsolescence of structures require a good management of building and infrastructure stock and include the challenging adaptation to new requirements via retrofitting, deconstruction or replacement (Kohler et al. 2009 p. 449).
Buildings are characterized by their immobility, heterogeneity and uniqueness. Due to their long lifespan, buildings are renovated, retrofitted or remediated by generations of users, residents and proprietaries over several decades to adapt the building to changing users' and environmental requirements. During their lifecycles, buildings are modified when different building elements and products are installed, removed or changed. Changes and modifications in immobile products such as buildings induce job shop production or project organization (Schultmann 1998 p. 141). In addition, some buildings cannot be economically adapted to changing requirements. The buildings in question undergo deconstruction (and replacement) processes, often in spatially limited

[1] Parts of this research contribution (especially section 2.3.1) were previously published in (Volk et al. 2014, 2015a; 2015b). Passages of these publications were developed exclusively by the author of this research contribution and are used without citation.

sites of dense urban areas, with limited resources available and under high time and cost pressure. Thus, the objective of the responsible decision makers in deconstruction projects is either makespan or cost minimization or both, depending on the building type and the preference of the decision maker. Often, these modifications of the building structure, equipment and fittings as well as the deterioration and contamination of buildings are not well documented. Thus, in many existing buildings, incomplete, obsolete or fragmented building information is predominating (Becerik-Gerber et al. 2012; Gursel et al. 2009) and result in partly unknown or uncertain building configurations. Also, media discontinuities in the building documentation exist during a buildings' lifecycle and are prone to errors and regularly associated with loss of data (Jehle et al. 2011).

Activities in the construction, retrofitting/renovation and deconstruction (C&D) sector induce large mass flows with massive impact on the regional environment. In the European Union and Norway, on average 31% of the generated waste can be assigned to C&D activities and about 60% of C&D waste is recycled by C&D industries (Fischer and Werge 2008). In Germany, these numbers are even higher with about 50% in 2007 (ARGE KWTB 2007; UBA 2009) to 58% in 2010 (BMU 2012b) of the annual waste amount that can be assigned to the C&D sector and which equals 2.5 to 2.9 tons of annual debris per inhabitant. Figure 1-1 shows the annual relatively constantly generated amount of mineral waste of the German C&D industry over the past two decades. 54.9 million t (68,5%) of the 80.2 million t of generated mineral waste on the long-term average is mineral debris, of which about 72% are recycled (ARGE KWTB 2015). Non-mineral construction site waste amounts to 8.8 million t (10.9%)[2]. Essential for the C&D waste management is the knowledge about the

[2] Recent studies show that until 2050 deconstruction waste will be larger than potential recycling paths in new construction in Germany (Schiller and Deilmann 2010). Reduced life expectancy of structures and building components (Kohler et al. 1999) also lead to accelerated retrofitting cycles and higher waste streams. This increases the relevance and need for strategies in the demolition waste management.

amount and composition of the „anthropogenic deposits“ and the waste streams of C&D activities (Rechberger and Clement 2011; Schiller and Deilmann 2010) both in detail and on aggregated level. Although a building inspection is mandatory before deconstruction according to the German federal construction regulations (Landesbauordnung), buildings with less than 500 m³ enclosed space are not affected by this regulation and are often not inspected or recorded (Knappe et al. 2012). Other buildings or special structures are partially exempted from reporting to the authorities (Knappe et al. 2012). However, numerous data gaps and uncertainties in existing buildings both on aggregate level and on building level are predominant (Kohler et al. 1999). And, missing or obsolete building information might result in ineffective project management, with uncertain process results, time loss or cost increase in maintenance, retrofit, remediation or deconstruction processes. However, troubleshooting in building documentation by elaborate building recordings or retrieval of lost data are associated with considerable additional time and expense (Jehle et al. 2011).

Moreover, increasing diversity of built-in building elements and materials in building fittings and equipment (Görg 1997) hamper retrofitting and deconstruction project planning and reutilization, recycling or disposal at the end of their lifecycles, e.g. of insulation or light-weight materials, hardly separable and recyclable non-mineral composites in pipes, sandwich elements or building automation systems, elevators, underfloor heating or photovoltaic elements. Also, the introduction of toxic or hazardous (asbestos, polycyclic aromatic hydrocarbons PAH, or polychlorinated biphenyls PCB) or quality reducing (gypsum, sulfate) materials and elements in the last decades as well as the risk of spreading of problematic substances due to unqualified material identification and separation are still an issue (Kohler et al. 1999 p. 2) in deconstruction projects.

Selective deconstruction[3] can foster the material separatrion and reuse and recycling of construction materials and building products/elements. Adequate remediation can induce preventive measures and lead to significantly cost increase and is still often neglected in practice. Additionally, legal regulations in the C&D waste area are vast and planned regulations like the MantelV might additionally tense the recycling or disposal conditions of secondary raw materials and debris from buildings and structures.

Figure 1-1: Annual mineral waste generation (without soil) from C&D industry in Germany[4], differentiated into waste fractions of construction site waste (dark grey), road scarification (light grey) and debris (grey)

Demographic changes and politically motivated limitation of land use also lead to increasing retrofits and replacements in urban areas (Koch and Schneider 1997). To cope with the challenges of high debris mass

[3] Selective deconstruction includes a demolition with partly preservation of neighboring building parts particularly taking future building and site/land-use into account via a “reverse construction process” (Lippok and Korth 2007) (see also section 2.1.2).

[4] (ARGE KWTB 2015).

flows and relatively low flows of recycling aggregate with respect to sustainability and resource efficiency, EU-regulations like 305/2011(55) postulate reuse or high quality recycling of building components. In Germany, conflicting environmental policy objectives are contrarily discussed (Dehoust et al. 2008 p. 1) that manifest in the planned MantelV regulation that decrees material qualities and recycling-hampering substances to protect soil and groundwater and thus limits C&D waste recycling options. Other political aims supporting mass flow reduction and recycling are the German national sustainability strategy and its related report[5].

In recent years, increasingly recycling, resource efficiency and urban mining research approaches are publicly funded, that use the anthropogenic sphere as a raw material source, such as German resource efficiency program ProgRess I/II (BMU 2012a; Bundesregierung 2011; EU Kommission 2011) or research programs r², r³ and r4 (BMBF 2013) to invent and improve secondary raw material extraction techniques, material treatments and recycling options. Both politics and research aim at converting linear mass flows to cyclic mass flows to preserve natural resources like climate, air, water, soil or landscape and anthropogenic resources like energy or financial resources. Additionally, the increased public ecological awareness leads to raised interest in resource efficient or environmental-friendly products, buildings and structures.

Set of problems

Buildings and modification projects related to buildings are usually associated with high uncertainties due to their unique characteristics (Girmscheid and Busch 2014 p. 3). Since the deconstruction of a building or infrastructure has project character, operative project management methods can be applied to plan, execute, control and evaluate projects under time, cost and resource constraints.

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[5] “Nationale Nachhaltigkeitsstrategie” and “Nachhaltigkeitsbericht”.

To use anthropogenic stocks efficiently, auditing and inventorying of single buildings and infrastructures with respect to their inherent raw materials are necessary to conduct an efficient deconstruction planning and executing under minimal cost, minimal project makespan or maximal resource recovery/recycling rate. The current deficits lie in the partly large mass deviations and the insufficient documentation of building configurations and the resulting non-determinism of buildings' debris (Görg 1997; Schiller and Deilmann 2010). This results in potential deviations in time and cost planning of activities as well as in recycling/disposal plans of deconstruction projects. Possible reasons are superficial site inspections under time/cost pressure, long lifetimes of buildings and building elements, deficient or obsolete documentation, or partly inappropriate bidding/tendering documents. This becomes even more obvious in building modification projects with increasing volume and complexity of the buildings and infrastructures in question from relatively homogenous single- and multi-family houses to large industry complexes or nuclear power plants. Improved methods are needed to more efficiently plan and manage deconstruction projects of buildings and to support decision makers in these types of projects, to face the deconstruction project planning and managing challenges with considerable deviations in building element mass estimation, space constraints onsite and changing information on building configuration in the course of the project and other risks and uncertainties.

Deconstruction planning is an essential part of the management and execution of deconstruction projects to plan time, cost, safety and environmental hazards (Chen and Li 2006). And, "compared to construction [projects], deconstruction planning of a building is more demanding in time, space, safety, and environmental regulation" (Liu et al. 2003). In the last decades, the importance of project management and multi-mode resource-constrained project scheduling (MRCPSP) increased and was thoroughly described in literature, such as in (Deblaere et al. 2008; Hartmann 2001; Hartmann and Briskorn 2010; Heilmann 2000). Moreover, efficient exact and heuristic solution methods for the MRCPSP have been developed (Bartels 2009 p. 1). Yet, there are only few works dealing with the application of this project planning method in deconstruction projects (Bartels 2009; Schultmann 1998). During the implementation of large remediation or retrofitting projects in constricted spatial conditions, a location-based planning approach might reduce timely overlap of working teams or storage and transportation of debris and dismantled elements in building wings or rooms. In lean construction, location-based planning gained in importance in construction projects and practitioners report up to 10% project makespan reduction (Lowe et al. 2012 p. 24). However, until now in deconstruction projects a location-based planning has not been applied yet.

Current deconstruction project planning approaches are deterministic and assume complete information, but projects are subject to uncertainty (Demeulemeester and Herroelen 2009; Herroelen and Leus 2004 p. 1599) and a very large percentage of projects fail to complete on time and budget because project parameters are seldom precisely known (Artigues et al. 2013 p. 201) and inherent risks were not taken into account (Munier 2014 p. 21). Also, during project execution the baseline schedule may suffer from disruptive events (Demeulemeester and Herroelen 2009) or information updates causing the activity start times to deviate from the original schedule and leading to common prolongations of project makespan. Thus, there is the need of considering uncertainties proactively to avoid later changes of project schedules after project disruptions. As time and cost pressure often lead to inadequate building auditing, the used planning criteria and deconstruction processes are also associated with uncertainty. For example, makespan and costs of projects in the construction industry deviate ± 20% from the original project plan (Girmscheid and Busch 2014 p. 3). During deconstruction planning and execution, considerable deviations in bill of quantities and cost estimations occur, leading to unexpected project prolongation and partly significant cost increase through sampling of hazardous elements, protective measures, idleness or quality loss of deconstructed debris. Experts in the associated research project estimate mass deviations between ± 5% for slabs, ± 20% for contaminated materials, and up to ± 40% for foundations. And, "in large projects, there could be thousands of tasks or activities that may be subject to delays and/or variations in cost, subsequently affecting the completion date and the estimated final cost of the project; most of the time, they are clear sources for threat" (Munier 2014 p. 21). Exceeding project deadlines in deconstruction often lead to high contractual penalties, due to expected delays of following activities (of other contractors) like remediation of soils, excavations or preparatory activities for new constructions. Until now, deconstruction project management approaches do not take uncertainties and risks occurring in existing buildings or changing information during project execution and related impacts on project makespan and cost systematically into account (Volk et al. 2014). But due to often lacking building documentation, it is necessary to identify uncertainties in building characteristics and element properties as well as to integrate them into project planning and to take their impacts on maintenance, renovation, retrofitting and deconstruction processes into account.

Deconstructors or contractors in deconstruction projects constantly face new challenges requiring adequate decisions and reactions (Lippok and Korth 2007). Thus, corporate risk management gains in importance in C&D industries (Issa 2013 p. 699; Lippok and Korth 2007 p. 81). Risk taking preferences of decision makers in the deconstruction industry differ and greatly influence the decision making process and the resulting impacts. But until now, risk preferences of decision makers often are not systematically integrated in decision support and planning systems for deconstruction projects.

And, the developments in recent years of digitalization and automation both in project management and the processes of the construction industry clearly show the increased research activities of and need for building modeling and various application areas, operative project planning, management and decision making tools, visualizations of building projects, and improved building auditing methods.

1.2 Aim, research questions and approach

Aim

The aim and targeted benefit of this research is the development and implementation of an operative project planning and decision support model to robustly plan building deconstruction projects that are subject to uncertainty and that enables and facilitates decision support under uncertainty (during auditing and execution). From the previously described set of problems, the following main requirements for the project planning and decision support model arise:

- The automated inventorying of buildings and the integration of existing buildings' uncertainties in their elements' properties shall improve the project planning. The systematic analysis and integration of uncertainties into deconstruction project planning shall depict their impact on deconstruction project execution and lead to more robust project schedules and budgets.
- The occurring spatial constraints onsite shall be included into deconstruction project planning so that locations of deconstruction activities are considered to avoid overlapping of teams, equipment and storage areas in confined spaces onsite and to reduce congestions and bottlenecks of teams and machinery.
- The risk preferences of decision makers shall be considered in deconstruction project planning and decision support to adequately evaluate alternative deconstruction schedules and plans.
- Information updates during project execution shall be included into the previously generated project plans and robust deconstruction strategies shall be recommended to the decision maker that includes the newly observed information on project conditions and building configuration.

Research questions

The following research question shall be answered that is of specific interest to decontaminators, deconstruction engineers and project managers, and experts working in deconstruction projects:

How can the selective deconstruction of a specific building be robustly planned under technical and spatial restrictions and uncertainty?

This question leads to further sub questions that are answered in this research contribution:

- What are the current project conditions in deconstruction industry?
- What are suitable project management approaches for deconstruction projects that consider uncertainty during project planning and project execution?
- What kind of uncertainties have to be considered in building auditing, building inventorying and deconstruction project planning and how can these uncertainties as well as time, cost, resource and space constraints be integrated into a model-based deconstruction planning and decision support model? What impacts are to be expected?
- How can robust deconstruction strategies be identified and decision makers' risk preferences be included into operative project management under uncertainty?

Approach

To answer the proposed research questions, the following approach is pursued and the remainder of the research contribution is organized as follows (see also Figure 1-2):
Chapter 2 provides an overview on building characteristics, the current legal, environmental, economic and technical conditions and state-of-the-art techniques in deconstruction projects that are necessary to anticipate, plan and manage deconstruction processes. First, this section includes a definition of key terms and concepts to assure a common

understanding of the terminology. Second, a short overview on legal and techno-economic conditions in the German deconstruction industry is given. This also includes an overview on state-of-the-art building auditing and documentation techniques as well as deconstruction techniques and their applicability under specific project conditions (materials, spatial or environmental conditions). A summary concludes chapter 2.

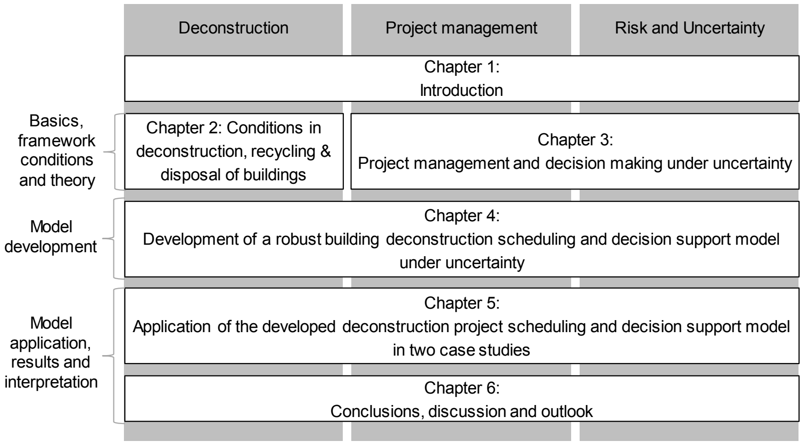

Figure 1-2: Graphical structure of this research contribution

Chapter 3 provides an overview on project management and decision making approaches in general and in deconstruction project planning in particular. First, key definitions of project management are given and an overview on currently available and used project management software and their capabilities is provided. Second, definitions of uncertainty, risk management and risk preferences are given. Third, project scheduling methods in literature are characterized and reviewed with their advantages and shortcomings regarding their consideration of uncertainty. Then, deconstruction projects are shortly characterized and a literature overview on deconstruction project planning approaches is given. This section is concluded by a summary.

Chapter 4 develops and details the deconstruction project planning model and decision support model. First, model requirements are formulated and a model overview is given. Then, the model parts are successively described. The first model part provides the identification of uncertainties in deconstruction planning to potentially anticipate time and cost increases caused by sample testing, preventive measures, choice of technology, process lags, ready and idle times, contractual penalties and quality reductions in recycling materials. To integrate uncertainties of different building configurations into a formal model, scenarios are defined. The second model part formulates the mathematical multi-mode resource constrained project scheduling problem (MRCPSP) for deconstruction projects and includes activity locations and differently qualified staff (multi-skill) as renewable resources. The third model part evaluates the found model results (schedules and strategies) from MRCPSP optimization for every scenario with respect to robustness criteria especially for risk-averse risk preferences. To consider changing information during project execution, the fourth model part includes a reactive project planning element that complements the previously identified robust baseline schedule in the case of schedule infeasibility due to a project disruption, an unexpected event or an information update.

Chapter 5 shows exemplary model applications in two case studies. The first case study covers the deconstruction planning of a four-room apartment, while the second case study describes the deconstruction planning of a part of a hospital. In these case studies, model applicability and result quality of the developed model is tested in the exemplary model application.

Chapter 6 displays a short summary, provides a discussion and critical appraisal of the presented approach, concludes the findings and gives an outlook on future research.

2 Conditions in deconstruction, recycling and disposal of buildings

The following chapter provides an overview on current framework conditions and state of the art of building deconstruction in Germany. To fully understand the challenges of deconstruction project planning, this chapter describes the most important deconstruction techniques, processes and organizational structures. The chapter includes three main sections. Section 2.1 includes definitions in deconstruction and recycling of buildings that are given for common terminology and for a better understanding. Furthermore, section 2.2 and section 2.3 describe legal and technical framework conditions that outline the vast amount of regulations concerning the deconstruction of buildings and the available deconstruction and recycling steps and techniques. These are decisive for the model implementation in sections 4 and 5.

2.1 Terminology in deconstruction, recycling and disposal of buildings

2.1.1 Definition of the deconstruction objects

Deconstruction processes differ widely with respect to the type and structure of the object that is deconstructed. Structures are differentiated into buildings and infrastructure. Buildings are further differentiated according to their use (see Table 2-1), construction type (see Figure 2-1), or construction year classification (see Table 2-2). Several sources differentiate the use type such as the „Bauwerkszuordnungskatalog“ (Bauministerkonferenz 2010; Bogenstätter 2007), the „Systematik der Bauwerke“ of the Federal Statistical Office (Kohlhammer 1978), the "Deutsche Gebäudetypologie“ of IWU (Diefenbach and Loga 2011; IWU 2005, 2012a; Loga et al. 2012) or the BKI system (BKI 2014). Table 2-1 shows a building typology according to Kohlhammer (1978) which is sufficient for the purposes of this research contribution. Residential buildings serve housing purposes, while societal buildings include constructions erected for trading, supply, education, administration, culture, healthcare and sports (Lippok and Korth 2007 p. 352).

Table 2-1: Typology of buildings with regard to kind of use[1]

Residential buildings
• Single family houses (SFH) • Multifamily houses (MFH) • Residential accommodation (RA)
Non-Residential buildings
• Office and administrative buildings • Factory and workshop buildings • Commercial buildings (warehouses) • Lodging facilities (hotels, restaurants, cantinas) • Educational buildings (schools, universities) • Traffic-related buildings (airports, train stations) • Medicinal buildings (hospitals, medical treatment institutes) • Agricultural buildings and other non-residential buildings (museums, theatres, libraries, churches, sport facilities, etc.)

In this research contribution, residential buildings (single family (SFH) and multi-family houses (MFH)) as well as similar non-residential, societal buildings with relatively simple configurations and structures are in the focus. The simpler building structures reduce complexity of the scheduling and decision making in deconstruction projects and enable simplified handling of data in the following problem formulation and solution approach. But, as the following model is implemented in an object-oriented manner, the method explicitly aims at extendibility on more complex structures such as diverse commercial, factory and workshop buildings or infrastructures.

1 According to (Kohlhammer 1978).

Figure 2-1 shows an overview on construction types in residential and non-residential societal buildings. Main construction types can be differentiated into solid, frame and precast construction where vertical (walls) and horizontal (slabs) construction materials are differentiated. Solid construction includes vertical structures from masonry, reinforced concrete or timber while the horizontal construction consists in reinforced concrete or timber slabs. Frame construction has a steel, reinforced concrete or timber frame structure where infills can consist in masonry or reinforced concrete. Horizontal slabs are made from steel, reinforced concrete or timber. In precast construction, precast building elements are pre-fabricated mainly from reinforced concrete, but also from timber or masonry for vertical construction elements (walls), while the horizontal slabs are made either from reinforced concrete or timber.

The main focus in this research contribution lies on building types (I) and (II) (except for pre-stressed concrete), because according to IWU (2012), these construction types constitute around 92% of the buildings older than 1978 in Germany (IWU 2012a; b). Building types (III) and (IV) are far less relevant with a share of 1,3% respective 4,4% of the German building stock (IWU 2012a; b) and might be considered in future research. A further extension of the model might include other construction types, especially those relevant in complex non-residential buildings or infrastructures.

Table 2-2 shows differing construction year classifications according to the literature. Various sources with different focus from the statistical survey, energy and material point of view refer to between three and eleven construction year classes. It becomes obvious that all classifications are oriented at the periods before and after the two World Wars of the 20th century. And, deconstruction-related sources like (Lippok and Korth 2007) consider less classes than classifications related to buildings' energy-efficiency (IWU 2005, 2011, 2012a; b; Loga et al. 2012). With respect to deconstruction planning, a classification of buildings into construction year classes might be problematic due to often lacking information on retrofit dates during their long use phases and often only assumed retrofits of buildings and elements.

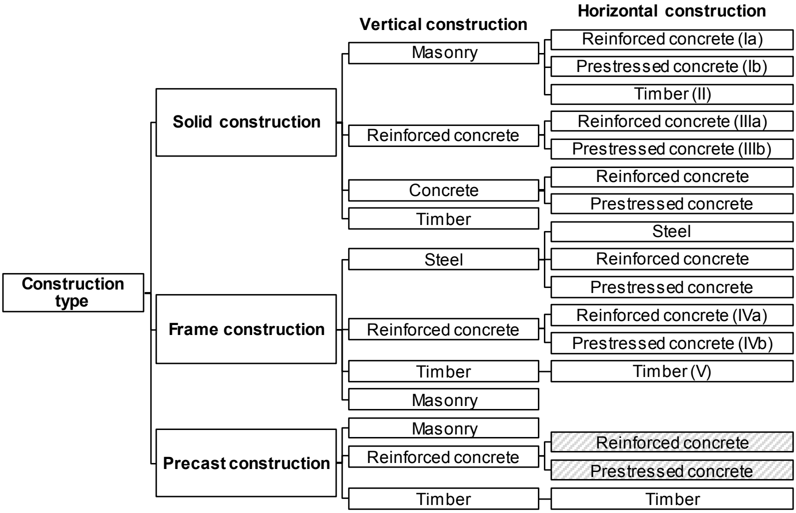

Figure 2-1: Typology of residential and non-residential buildings with regard to their type of construction[2]

However, it is not possible to generalize a buildings' configuration and assign it to a certain type as there are both different construction year classifications of residential buildings in Germany and often seldom information about their retrofitting. Further differentiation of buildings according to building height, gross volume (BRI) and number of (residential) units can also be applied. Thus, for each building that will be deconstructed, a separate building auditing is required to gather the unique building information on inherent building elements, building materials and volumes.

2 According to (DBU 2014; Lippok and Korth 2007 p. 352; Toppel 2004 pp. 53–59).

Table 2-2: Typology of buildings with regard to different construction year classifications of residential buildings in Germany

Source	(Görg 1997; Kohlhammer 1978)	(Kohler et al. 1999)	(Deutscher Abbruchverband e.V. 2015; LfU 2001)	(Klauß et al. 2009)	(Schiller and Deilmann 2010)	(May 2011)	(IWU 2005, 2011, 2012a; 2012b; Loga et al. 2012)
Focus	statistical survey	material	material	material	material	statistical survey	energy
Construction year classes	before 1918	before 1870	before 1918	before 1918*	before 1918	before 1900	before 1859
		1871-1918				1901-1918	1860-1918
	1918-1945	1919-1949	1918-1948	1919-1948	1919-1948	1919-1948	1919-1948
	1946-1955	1950-1964	ab 1949	1949-1957	1949-1968	1949-1962	1949-1957
	1956-1970	1965-1976		1958-1968		1963-1970	1958-1968
	1971-today	1977-1991		1969-1978	1969-1990	1971-1980	1969-1978
				1979-1983		1980-today	1979-1983
				1984-1990			1984-1994
					1990-2005		1995-2001
							2002-2009
							2010-today
	*: differentiation in frame and solid construction **: without special cases, e.g. in East Germany (new federal states) with precast construction						

2.1.2 Definitions in the deconstruction process

Demolition, deconstruction, dismantling or disassembly are defined in several ways in literature: In the following, demolition is the partly or complete removal of technical and/or constructional structures or parts both in a conventional and selective way (Lippok and Korth 2007). Generally, the demolition process can be separated into two stages: selective deconstruction (gutting) of specific building elements (including valuable or hazardous elements) and the demolition itself including the destruction of the main building structure (see also Figure 2-4). Selective dismantling focuses explicitly on the material- or building element specific auditing and removal (recycling/disposal) of deconstruction materials or elements that comes along with an often higher time effort due to mainly manual separation activities (Lippok and Korth 2007). Dismantling also describes the process of loosening (frictionally engaged) element connections in buildings or structures and to deconstruct the structure via lifting whole building elements with the purpose to re-use them (Lippok and Korth 2007).[3] Selective deconstruction includes a demolition with partly preservation of neighboring building parts particularly taking future building and site/land-use into account via a "reverse construction process" (Lippok and Korth 2007). In literature, selective deconstruction, dismantling and disassembly are often used synonymously. In this research contribution, the terminus deconstruction is used synonymously with selective deconstruction, dismantling or disassembly.

The degree of (selective) deconstruction describes the degree of separation of the building inherent materials and especially of building elements into mono-material (waste) fractions with minimum deconstruction and recycling cost (Spengler 1998). New sustainable residential and administrative building construction guidelines already include the dismantling or deconstruction friendliness of the building in terms of the deconstruction degree into design considerations and building quality ratings and propose the creation of a detailed deconstruction concept with the required building information and proposed deconstruction techniques (BMU 2015; NaWoh 2013).

In the course of a structures' deconstruction, respective waste fractions are induced. Waste fractions can be divided into debris, construction waste and road construction waste. Debris includes mineral materials (incl. minor non-mineral impurities) while, construction waste contains

[3] Similar termini like ordered or controlled deconstruction, disassembly, site clearance, coring/gutting or clearing out are differentiated in (LfU 2001; Lippok and Korth 2007) or in DIN 18459:2015-08.

mixed non-mineral material (incl. minor mineral impurities) (Deutscher Abbruchverband e.V. 2015). In this research contribution, the focus lies on both mineral and non-mineral waste fractions that are generated during selective deconstruction in the sense of a "reverse construction" of buildings (see also section 2.1.4).

The deconstruction of a building takes place in several stages and requires several activities using different machinery onsite (see section 2.3 for a comprehensive description of the deconstruction process). Thus, a deconstruction process can be classified as a multistage, divergent, discontinuous job shop production process producing locally unbound formed and unformed material goods (Schultmann 1998; Spengler 1994), e.g. recycling elements, recycling material and waste. Job shop production and scheduling following the functional principle, which includes several tasks performed at the same objects such as separating, dismantling, crushing, sorting or loading of building elements. Due to the uniqueness of each building, it is a single part or job shop process with make-to-order production performed at client's request. Deconstruction of buildings includes mainly physical and divergent production processes. Also, the work or production site is changing and leads to respective transportation and logistics of resources to each site.

2.1.3 Definitions of resources and contaminations

Resources are differentiated into natural resources such as water, air or soil and artificial resources such as raw materials, labor, capital, energy or land. With respect to deconstruction projects, consideration of both natural and artificial resources is essential. Legal frameworks are designed to protect natural resources, while the use of artificial resources is minimized or their recycling (raw materials, land) is maximized.

Raw materials are substances or mixtures in raw or slightly processed state that can enter a production process (Kosmol et al. 2012). Buildings and their elements (building products, equipment, separation layers etc.) consist of building (element) materials that are raw materials, substanc-

es, mixtures or compounds. Recycling building materials (RC materials) are mostly mixtures of aggregates that were used in elements of buildings or infrastructures before (Dehoust et al. 2008 p. 27).
The generated building elements and materials in deconstruction projects are manifold and have to be reused, recycled or disposed. Main materials include concrete, natural stone (gravel, sandstone), brick and roof tiles, cellular concrete brick, sand lime brick, mortar/ plaster/ screed, gypsum (cardboard), tiles and sanitary ceramics, steel, non-iron metals (copper, aluminum, lead, zinc), glass, timber, plastics (PE, PVC), insulation materials, cables and electronic waste, textiles and hazardous materials. An short overview on the main materials and their use in building elements is given e.g. in (Toppel 2004 pp. 60–78). Hampering substances (see Figure 2-2) hinder the efficient recycling of building elements and materials (Lippok and Korth 2007), such as gypsum/sulfate (Weimann et al. 2013). Hazardous materials are substances that already can affect or harm humans and environment in low concentration (Lippok and Korth 2007). Hazardous materials are numerous and can be differentiated into natural and artificial materials and the latter into primary and secondary hazardous materials (see Figure 2-2) (Kosmol et al. 2012; LfU 2003; Lippok and Korth 2007; VDI 2013). While primary hazardous materials result from substances used in building element or building material production, secondary hazardous materials result from contamination during building use (LfU 2003; Lippok and Korth 2007; VDI 2013). Furthermore, ca. 100 harmful substances especially related to operational safety are listed in GISBAU (BG Bau 2013) and AGÖF (AGÖF 2013) with their concentration, exposure risks and disposal categories in the European Waste Catalogue (EWC). The existence of hampering and hazardous substances is often uncertain and has great impact on (expected) project makespan and cost.[4] The quantification of hazardous

[4] For further information and guidelines on decontamination and deconstruction with contaminated elements see (DBU 2014; LfU 2003; VDI 2013) and section 2.2 for their legal regulation.

materials and impurities in buildings still is problematic and requires a systematic approach and profound research, analysis and testing (Kohler et al. 1999 p. 12ff.; VDI 2013). Major hazardous issues are found in auxiliary building materials as well as compounds that mainly are contaminated and problematic for recycling processes (Kohler et al. 1999 p. 18).

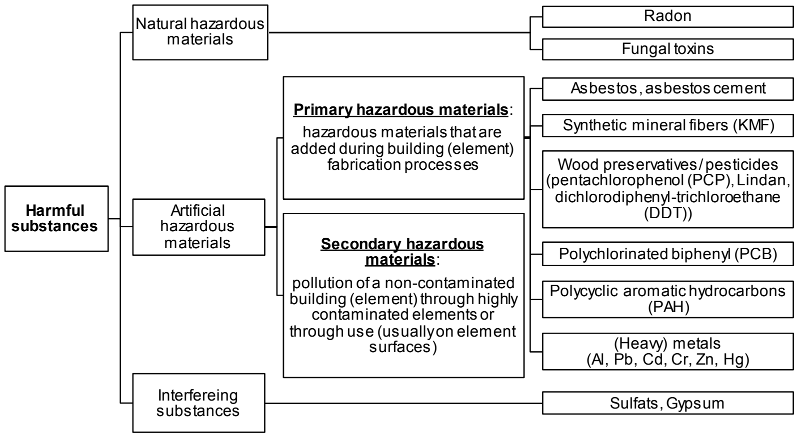

Figure 2-2: Classification of main hazardous and interfering substances/materials in building elements[5]

Primary hazardous materials (except for PAH in chimneys/funnels) can be easier considered in building auditing and project planning. Secondary hazardous materials are more difficult to identify, because the differing uses of buildings over their lifetimes often are not documented. Most primary hazardous materials can be expected to be related to interior fittings, such as sealing and insulation elements[6].

5 According to (AGÖF 2013; Berg et al. 2010; LfU 2003; Lippok and Korth 2007; Rötzel 2009; VDI 2013).

6 See Table 7-1 for potential sources of hazardous materials according to literature. An overview on occurring hazardous building elements can be found in (Berg et al. 2010; LfU 2003; Lippok and Korth 2007; Rötzel 2009; Zwiener 1997).

Currently, hazardous materials and building elements are supposed to be largely or completely removed during deconstruction preparation prior to building deconstruction.

2.1.4 Definitions in recycling and disposal

According to the recycling hierarchy of the German Kreislaufwirtschaftsgesetz (KrWG)[7], the recycling and disposal options for non-contaminated building materials and elements are: (1) avoidance, (2) reuse, (3) recycling (material), (4) recycling (filling, energetic) and (5) disposal: Reuse of a building element or materials depicts the use according to original or another use (Lippok and Korth 2007) in equal or slightly modified shape. In literature, recycling (RC) is defined in various ways. Mostly, recycling is defined as backflow (recycle) of materials into the material cycle resp. as secondary raw materials usage (Kosmol et al. 2012; Lippok and Korth 2007). However, literature disagrees if the energetic use or backfilling defined in KrWG can also be called recycling (EU Parlament and EU Rat 2008; Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz – KrWG) vom 24. Februar 2012. The Kreislaufwirtschaftsgesetz (KrWG) and the EU directive 2008/98/EG consider secondary energetic use and backfilling separately (KrWG 2012). In practice, there are different ways of recycling such as "from building construction to building construction" via RC material/elements or „from building construction to other construction applications" e.g. infrastructure in the form of aggregates from tiles, brick or concrete (see also Table 2-10). Backfilling is performed, if reprocessed or non-reprocessed aggregates stemming from deconstruction are used in infrastructure construction, mining or in landfilling (Lippok and Korth 2007 pp. 246, 438) without explicitly using their special material properties. Main motivation for recycling of building materials are the minimi-

[7] See section 2.2 for details on KrWG.

zation of landfill volume and the avoidance of pollutants entering soils; secondary motives are saving of natural resources and energy as well as the reduction of land use by open-cast raw material mines (Martens 2011 p. 212f.)[8].

The previously given definitions of building deconstruction projects and related areas in this subsection are used in the following. The next subsection describes the legal framework of deconstruction projects in Germany.

2.2 Laws and standards in building deconstruction and recycling

The deconstruction, reprocessing, treatment, recycling and disposal of buildings and infrastructures affect many environmental issues such as treatment of waste and hazardous materials, the protection of water, soil and air, pollution control and liability for environmental damage. Thus, a short overview on the legal situation in the EU and Germany is given in the following subsections. In Europe, environmental legislation is mainly passed by the EU, and member states are allowed to tighten regulations. Due to the federal structure in Germany, (de-)construction, waste and hazardous material regulations are realized on and differ at national, state and even communal level. This makes the legal aspects of deconstruction projects more complicated as the application of (local) regulations depends on the location of the site. Thus, deconstruction activities need to fulfill many regionally differing legal regulations on EU, national and regional level that are detailed in the following subsections.

[8] See e.g. (Dehoust et al. 2014; Martens 2011) for a comprehensive overview on component connections as well as materials and their recycling techniques.

2.2.1 Regulations for building deconstruction and recycling in the EU

In the European environmental legislation, there are several regulations that set the framework conditions for the handling and manipulation of building elements and building products that are partly conflicting with other environmental objectives e.g. preservation of climate, air, water or soil. Political activities cumulated 2011 in the flagship initiative 'Europe 2020 Strategy' for a resource-efficient Europe. This initiative aims at augmenting the economic performance and competitiveness while lowering the related consumption of resources (EU Kommission 2011).

The EU commission identified, amongst others, the building sector as key regarding the reduction of resource consumption (BMUB 2011) due to its high mass and energy flows. To improve resource efficiency, recycling economy and waste management, the EU Directive on Waste 2008/98/EG of the European Parliament and Commission from 2008 on waste is the legal framework for handling waste in the EU (EU Parlament and EU Rat 2008). Therein, key definitions are given for waste, recycling and disposal as well as a compulsory waste treatment hierarchy. The constantly updated European Waste Catalogue (EWC) and Hazardous Waste List from 2001 classify wastes and determine their hazardousness. Regulations like EU regulation 305/2011 (EU-BauPVO) (replacing regulation 89/106/EWG) state harmonized assessments of building products, elements and materials to lower trade barriers. This also affects recycling products that are designated to be placed in new constructions. Their adequate application in buildings is specified in national or local requirements e.g. in the German 'Landesbauordnungen'. Further exemplary regulations that affect building deconstruction are: EU regulation 1013/2006/EG on waste transportation (EU Parlament and EU Rat 2006) or EU regulations 715/2013 (EU Kommission 2013) and 333/2011 (EU Rat 2011) on the determination of waste.

2.2.2 Regulations for building deconstruction and recycling in Germany

Since 1974, numerous environmental EU regulations regarding waste handling, recycling and disposal have been approved and implemented in national law (Lippok and Korth 2007 p. 94) to protect soil (Dehoust et al. 2008 p. 1), water, air, landscape and to regulate waste handling. An overview can be found in (ESV 2014). Main legal regulations relevant for building deconstruction and wastes from C&D activities are the Abfall-rahmenrichtlinie including the Abfallverzeichnisverordnung (AVV=EWC) and the Kreislaufwirtschaftsgesetz (KrWG). Figure 2-3 and Table 2-3 show the main laws that are touched by deconstruction of buildings and structures, such as: waste collection and transportation, waste recycling and disposal. It becomes obvious, that the main regulation is KrWG however the laws on soil protection, water protection and immissions are also relevant for deconstruction projects. More specific regulations of waste treatment and recycling can be found in the sub regulations of KrWG that vary between the federal states. In the following, the main regulations that affect building deconstruction projects are shortly described.

Relevant standards, guidelines and technical regulations are discussed in section 2.3. Further regulations include regulations on occupational safety (Lippok and Korth 2007 p. 50f.) such as TRGS guidelines or on liabilities (Lippok and Korth 2007 p. 81), which are not subject of this research contribution and thus neglected in the following. However, as this research contribution does not focus legal issues, for further reading the reader is advised to (Schultmann 1998) for the development of the legal situation in the 1990ties and to (Berg et al. 2014; Deutscher Abbruchverband e.V. 2015 pp. 106–133) for the current legal situation in Germany.

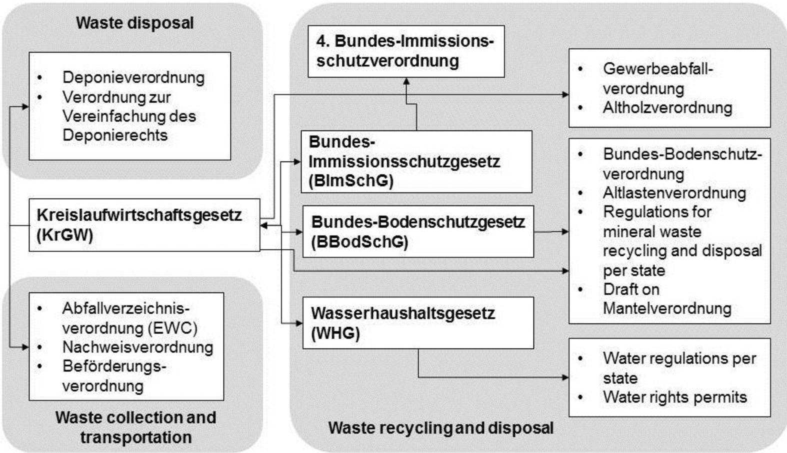

Figure 2-3: Overview on the relevant laws in Germany for building deconstruction[9]

In 1972, the first German law for the handling of waste (KrW/AbfG) was enacted with its sub regulations, for the first time the framework conditions for public waste management (Schultmann et al. 2001). In 2012, it was replaced by the ‚Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz – KrWG)' of 24.02.2012 (BGBl. I p. 212) (KrWG 2012). The §6 of KrWG defines the recycling hierarchy of waste with: 1. avoidance, 2. preparation for reuse, 3. recycling, 4. other recycling, especially energetic use and backfilling and 5. disposal. Starting from 01.01.2020, recycling of at least 70 % (mass) of non-hazardous construction and deconstruction waste is required by law in §14 (3) of KrWG (status: 01.06.2012). However, the term recycling is not clearly defined yet and may also include backfilling or energetic use. In 2007, a simplification of waste regulations was applied to align to EU regulations and to implement the electronic waste registration and tracking (BMU 2007).

[9] According to (Deutscher Abbruchverband e.V. 2015 p. 116; Lippok and Korth 2007 p. 95).

Table 2-3. Overview on legal regulations in building deconstruction, recycling and disposal of debris of buildings and infrastructures[10]

	Deconstruction/ dismantling/ disassembly			**Recycling/ Disposal**		
	Pre-planning	**Bidding**	**Execution**	**Occupational safety**	**Transport/ Transfer**	**Recycling/ Disposal**
non-hazardous building materials/ elements	KrWG LAbfG BaustellV DSchG	BGB § 613ff VOB	LBO LBOVVO BaustellV DSchG	ArbStättV ArbSchG	KrWG NachwV TgV BauPG	KrWG BestbüAbfV NachwV BauGB
hazardous building materials/ elements	KrWG LAbfG BaustellV DSchG	BGB § 613ff (Werksver-trag) VOB[11]	LBO LBOVVO BaustellV DSchG	ArbStättV ArbSchG TRGS 519 TRGS 521 LAGA M23 GefStoffV	KrWG NachwV TgV	KrWG BestbüAbfV NachwV BBodSchG BBodSchV TR der LAGA ChemG ChemVer-botsG BestbüAbfV 4. BimSchV

ArbSchG:	Arbeitsschutzgesetz
ArbStättV:	Arbeitsstättenverordnung
BauGB:	§179, Bauordnungen der Bundesländer
BauPG:	Gesetz über das Inverkehrbringen von und den freien Warenverkehr mit Bauprodukten
BBodSchG:	Gesetz zum Schutz vor schädlichen Bodenveränderungen und zur Sanierung von Altlasten (Bundes-Bodenschutzgesetz)
BBodSchV:	Bundes-Bodenschutz- und Altlastenverordnung
BestbüAbfV:	Verordnung zur Bestimmung von bes. überwachungsbedürftigen Abfällen
ChemG:	Gesetz zum Schutz vor gefährlichen Stoffen
ChemVer-botsV:	Verordnung über Verbote und Beschränkungen des Inverkehrbringens gefährlicher Stoffe, Zubereitungen und Erzeugnisse nach dem Chemikaliengesetz

[10] According to (Deutscher Abbruchverband e.V. 2015; LfU 2003)

[11] The VOB changes in 2002 regarding deconstruction/disassembly of buildings are discussed in detail in (Lippok et al. 2004).

DSchG:	Gesetz zum Schutz der Kulturdenkmale
GefStoffV:	Verordnung zum Schutz vor gefährlichen Stoffen
LAbfG:	Landesabfallgesetz
LAGA:	Bund/Länder-Arbeitsgemeinschaft Abfall
LBO:	Landesbauordnung
LBOVVO:	Verfahrensverordnung zur Landesbauordnung
NachwV:	Verordnung über Verwert.- und Beseitigungsnachweise
TgV:	Verordnung zur Transportgenehmigung
TRGS:	Technische Regeln Gefahrstoffe
VOB:	Verdingungsordnung für Bauleistungen

In practice, building materials, waste and RC materials are differentiated. Building materials and elements are classified according to their handling and toxicity in GISBAU. Construction and deconstruction waste is classified according to the constantly updated European Waste Catalogue (EWC) respective "Abfallverzeichnisverordnung" (AVV). Moreover, LAGA M20 describes several material qualities that define RC material applicability/usability of mineral material. Further sub-categories (waste fractions) are applied at the reception of recycling and disposal facilities. The regulation on the determination of waste for requiring supervision (BestüVAbfV) is a sub-regulation of KrWG regarding specific materials that are listed in the regulation. Furthermore, the generated building elements and materials remain in the ownership of the client (DIN 18459:2010-04, 2.1) which has important legal and contractual consequences.

In deconstruction processes, the technical guidelines (ATV DIN 18299:2012-09 VOB/C, DIN 1960:2012-09 VOB/A) and professional association guidelines (arbeitssicherheit.de 2013; BG Bau 2013) for general construction apply. These are complemented by the technical guidelines specifically for deconstruction DIN 18459:2010-04 VOB/C (German construction contract procedures (VOB) – Part C: General technical specifications in construction contracts (ATV) – Demolition and dismantling work) edited by Deutscher Abbruchverband. DIN 18459:2010-04 regulates the contractual procedures in deconstruction projects that include the whole or partly deconstruction of buildings or structures including transportation, storage or loading activities. DIN 18459:2010-04 also includes the state-of-the-art deconstruction techniques with regard to the available service descriptions, the scope of application, materials and components, execution of deconstruction services, fringe benefits and special services as well as accounting issues (Lippok and Korth 2007). It also includes reference units per building elements (per construction type, e.g. [piece, m, m², m³]) for the calculation, the planning and bidding of projects (see Table 2-4). For example, unit [m³] is applied for the calculation of deconstruction times and deconstruction costs of buildings' foundations. If unexpected building elements, materials or constructions are detected during the course of the project, contingency measures are to be defined with the client and are billed as additional/special services (DIN 18459:2010-04, 3.3.3). Furthermore, several reductions from the inventory volumes and quantities and the buildings' spatial indicators (GV, GFA) have to be applied (see Table 2-4, right column).

As supplementary claims for deviations of material masses (more/less than +/- 10% compared to the contracted bill of quantities and service description according to (§ 2, No. 3, Sec. 2 VOB/B)) due to plan changes or additional services are very important in practice (Deutscher Abbruchverband e.V. 2015 p. 110).

DIN 18007:2000-05 defines the rather technical issues such as different deconstruction techniques and their applicability with regard to building elements and materials. Furthermore, VDI/GVSS 6202:2013-10 and technical guidelines for job safety (TRGS) apply for deconstruction, remediation and retrofitting measures especially of hazardous building elements, equipment and materials.

The sub regulation Gewerbeabfallverordnung (GewAbfV) prescribes the requirement of separate storage of certain waste fractions from building construction and deconstruction activities (Knappe and Lansche 2010 p. 42). Moreover, both client and deconstruction operator are responsible for the appropriate waste disposal according to §5 Sec. 2 (GewAbfV)

and §11 Sec. 1 (KrWG). Further regulations address the generation and treatment of specific waste fractions (electrical appliances: Elektro-StoffV, used timber: AltholzV, used oil: AltölV).
The Abfallverbringungsgesetz (AbfVerbrG) is the German realization of EU regulation 1013/2006 of 14.06.2006, the 'Accord européen relatif au transport international des marchandises Dangereuses par Route' (ADR) and the Basel convention of 22.03.1989 on the control of transboundary shipments of hazardous waste and their disposal. It also regulates the shipment and elimination of hazardous materials from the place of generation (here: deconstruction site) to the elimination site within the federal territory or in connection with an EU transit. The domestic elimination of the hazardous substances is to be preferred over the disposal abroad. For the disposal of deconstruction wastes, the regulations and waste classifications of Deponieverordnung (DepV) into disposal classes I, II, III have to be applied. To receive a certificate of waste management associations, deconstructors and recyclers also have to fulfill regulations of the Entsorgungsfachbetriebe-verordnung (EfbV).
The Gefahrstoff-Verordnung (GefStoffV) (changed on 03.02.2015) regulates e.g. the management and disposal of highly flammable, toxic, corrosive or carcinogenic substances such as polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT), Pentachlorophenol (PC) or asbestos occurring in building deconstruction. Furthermore, specific regulations exist for several hazardous materials (e.g. PCBAbfallV, PCB-Richtlinie, Asbest-Richtlinie) and procedures are also further specified in the guidelines BGR 128 and TRGS 524. Also, the Biostoffverordnung (BiostoffV) might be applied when non-specific contact (§6 BiostoffV) is made to infectious, sensitizing or toxic substances, e.g. parasites, fungus and pigeon droppings in deteriorated buildings that will be deconstructed.

Table 2-4: Reference units per building elements [12]

Reference unit	Building elements	Reductions
Cubic measure [m³]	• Foundations and foundation slabs, ceilings, walls • Pillars, beams, truss beam, rafter etc. • Abutment, ramps, staircases • Liquids	• Notches / recesses above 0.5 m³ single size
Square measure [m²]	• Foundations and foundation slabs, (separation/ partition) walls, ceilings, • Floor, walls or ceiling coverings, plaster, tiles, screeds, • Insulation, claddings, roofing • (Thermal, high pressure) cutting according to cutting surface • Milling, grinding according to surface • (Partly) Steel cutting according to surface [cm²]	• Notches, recesses, openings above 2.5 m² single size • Notches in floors above 0.5m² single size • Gaps in the surface that will be deconstructed above 0.3m (e.g. pillars, trusses etc.) • Cutting surfaces with interruptions above 0.1m² single size
Linear measure [m]	• railings, parapets • pipes • trimming/edging, drilling, trenching, separating cuts	• None
Number [pieces]	• Windows, doors • Wall and ceiling breakthroughs, • Containers, tanks, radiators, heating systems etc., • Lamps, fluorescent tubes, capacitors	• Interruptions above 1m single size (except core drilling)
Mass [kg], [t]	• According to building materials	• None

Furthermore, in the discussion of recycling building elements and materials further regulations apply which are shortly addressed here but not focus of this work. Since July 2013, the Bauproduktengesetz (BauPG) and Bauproduktenverordnung (BauPVO) as a realization of EU directive 305/2011 (formerly: 89/106/EWG) in Germany regulate the marketing and trade of construction materials in the EU. Building products are

[12] According to VOB DIN 18459:2010-04, 0.5.

mostly traded between professionals and their adequate application in buildings is regulated. EU members are allowed to specify other national or local requirements e.g. in Germany in their federal Bauordnungen (Landesbauordnungen[13]) that also specifically regulate the use and trade of building products in the designated areas. In particular, the usability of recycled materials or recycled building products or elements has to be proven according to the described regulations, which is a time-consuming and expensive procedure which significantly hampers the use of RC materials and RC elements. Furthermore, for each main building material such as (reinforced) concrete, there are further standards e.g. by Deutscher Ausschuss für Stahlbeton e.V. that need to be fulfilled. Also, the Produktesicherheitsgesetz (ProdSG) (enabled in 01.01.2012) might be relevant regarding safety issue and requirements of recycled products. As Bodenschutzgesetz (BBodSchG) was passed in 2004, it became clear that new technical concepts of soil and groundwater protection beyond LAGA M20 were needed regarding the use of mineral materials and waste (Dehoust et al. 2008 p. 1). Since then, the Ersatzbaustoffverordnung (ErsatzbaustoffV, Art. 2 of MantelV) is thoroughly and controversially discussed with respect to different objectives (Dehoust et al. 2014; Grathwohl 2011; Susset and Leuchs 2011). On the one hand, the Ersatzbau-stoffV aims at further enhancing the protection of soil and water and on the other hand tries to increase recycling rates of construction and deconstruction waste (mainly mineral fraction). At the time of publication, there was no nationwide agreement on standard threshold values for recycling materials, as well as their classification and qualities beyond the applied values of working group LAGA M20 for mineral waste fractions[14].

[13] German Landesbauordnungen can be found on http://www.bauordnungen.de/html/deutschland.html (accessed: 19.05.2016).

[14] However, other countries like Austria further restrict their regulations (new Recycling-Baustoffverordnung) to an obligatory analysis of hazardous materials by an authorized person for each building that will be deconstructed and an obligatory reuse/ recycling for the resulting masses starting in 01.01.2016 (BRV 2015).

The federal working group 'LAGA' has developed releases and bulletins for the classification and treatment of construction and deconstruction masses for several material and wastes, such as the LAGA M20 (Requirements for recycling mineral waste, 06.11.2003), LAGA M23 (Requirements for the elimination/disposal of waste containing asbestos, 25.09.2002), LAGA M25 (Requirements for waste shipments, 30.09.2009), LAGA M31 (Requirements for disposal of electric and electronic equipment, EAG) or LAGA M32 and M33 regarding the procedures for physical, chemical and biological investigations in connection with the recycling / disposal of waste, contaminated soils and materials in remediation processes, 01.01.2002). Furthermore, LAGA M34 provides further instructions on the national Gewerbeabfallverordnung (GewAbfV, 01.03.2008). LAGA M36 provides further instructions on the Entsorgungsfachbetriebeverordnung (EfbV, 19.05.2005). Furthermore, the 'Technische Regeln Boden' regulates the definition, the investigations and the handling of soils regarding recycling, use or disposal (TR Boden, 05.11.2004).

2.2.3 Regulations for building deconstruction and recycling on regional level

On regional level in Germany, there are numerous regulations that differ between federal states and communes. Here, national law is concretized in federal laws and federal building codes e.g. in Baden-Württemberg the Landesabfallgesetz (LAbfG) (17.12.2009) and the respective Landesbauordnung (see also section 2.2.2). The Landesbauordnung also defines in §49 if a deconstruction project requires a construction or deconstruction compulsory registration and permit by local authorities or define deconstruction fees. In addition, in each local authority district there are municipal/communal statute laws with regionally differing waste statutes and fee statutes that vary drastically. Permit-free deconstruction projects are the deconstruction of agricultural and forestry equipment up to 5m height, buildings up to 300 m³ gross volume as well as structures and buildings with permit-free construction according to the respective Landesbauordnung (Knappe and Lansche 2010 p. 42). For all other deconstruction projects and demolition works, authorities have to be informed about the measures by the building owner (§51, 52 in Landesbauordnung). If there is no objection of the authority within a certain period, the deconstruction project can be realized (Knappe and Lansche 2010 p. 42). In practice, there are no specific regulatory obligations regarding the handling of deconstruction materials and wastes beyond the handover of respective information sheets (Knappe and Lansche 2010 p. 42).

In summary, deconstruction projects are affected by many regulations on national and regional level, that have an influence on the used deconstruction techniques, the recycling and disposal options or the deconstruction activity precedences in a project. It is important to understand these circumstances that are considered in the following as framework conditions for the developed decision making model. In the following subsection, state of the art deconstruction processes and techniques are described following the main deconstruction project phases.

2.3 Techno-economic conditions and state-of-the-art building deconstruction and recycling

The deconstruction process can be divided into several consecutive project phases: bidding, auditing and planning, preparation (decontamination, site clearance), deconstruction, recycling and disposal, and controlling[15]. Figure 2-4 shows schematically the main deconstruction project phases and their main issues and the consecutive material handling options which form the structure of the following subsections. As the bidding phase with its contractual relations between client and contractor is not in the focus here, it will not be further described but

[15] See (Lippok and Korth 2007 pp. 18–21) for more detailed process steps.

refer to (Deutscher Abbruchverband e.V. 2015; Toppel 2004 pp. 116–120) for a profound description. In the following subsections, the project phases of auditing (section 2.3.1) and planning (section 2.3.2), the preparation (section 2.3.4), deconstruction (section 2.3.5) and recycling and disposal (section 2.3.6) are described in detail. In this research contribution, main focus lies on the auditing and planning of the preparation and deconstruction project phases.

2.3.1 Building auditing[16]

The building stock can be regarded as an interim storage of building materials and building elements and as resource for future building materials, products and elements (Behnisch 2008). When buildings reach the end of their current use phase, auditing for retrofitting or deconstruction purposes is necessary. There are top-down and bottom-up approaches for quantifying resources and materials in (German) building stock. Top-down approaches try to quantify building material masses via the construction type of a building and the multiplication with material mass factors. Bottom-up approaches, as considered in this research contribution, focuses on auditing of all elements inherent in a building that are aggregated to a building inventory. The interested reader can find top-down approaches e.g. in (Buchert et al. 2004; Dirlich et al. 2011; Schiller and Deilmann 2010).

The design, planning and performance of deconstruction measures in Germany is based upon site inspection, exploration of contaminations, documentation review and auditing of the building by the building owner or planning engineer. If properly done, existing building elements, site conditions, space availability, mass calculation and other conditions relevant for deconstruction are collected (Lippok and Korth 2007; Rommel et al. 1999). Table 2-5 shows the main documentation subjects that are sources of building information during building auditing.

[16] Parts of this section regarding BIM have been previously published in (Volk et al. 2014).

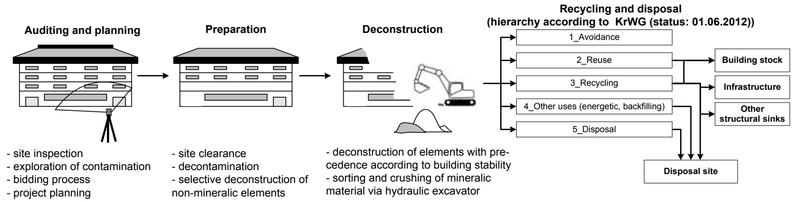

Figure 2-4: Main deconstruction project phases[17]

Capturing this information can be done manually, semi-automated, automated, terrestrially or aerially, depending on the buildings' or structures' size and complexity. Currently, building auditing is mainly performed manually. The manual auditing includes a site inspection, manual measurement of the building (gross volume) and its elements as well as the examination of existing building documentation and photos often performed with checklists. Semi-automated capturing of building information is performed by laser scanners, photogrammetric methods or tagging of RFID or barcodes. Automated building auditing would additionally include the self-generation of digital building information models (CAD, BIM)[18] and/or building inventories. Semi-automated or automated auditing requires the digitalization of current approaches such as manuals, checklists, guidelines and measurements in the form of ontologies and machine-interpretable rules. Terrestrial building auditing and capturing is mainly carried out at individual building, while the aerial detection is performed on larger building stocks, areas or infrastructures.

[17] According to (Abdullah and Anumba 2002a; b; Chen and Li 2006; Lippok and Korth 2007 pp. 18–21).

[18] For information on BIM see standards like PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling, ISO/TS 12911:2014 Framework for building information modelling (BIM) guidance, ISO 29481 Building information modelling - Information delivery manual, DIN SPEC 91400:2014 BIM-Classification according to STLB-Bau, US standard of buildingSMARTalliance, COBie standard, NIBS standard etc. For state-of-the-art BIM in Germany see (Egger et al. 2013) and for application in new buildings on international level see the work of working group CIB W78 (http://cib-w78-2015.ddss.nl/index.html).

Guidelines for retrofitting (Vismann 2012 p. 1200), deconstruction (LfU 2001, 2003; Rommel et al. 1999; Wangler et al. 2010) and remediation (VDI 6202-Blatt 1: 06-2012) propose checklists for building inventory and survey, but an unitary approach is lacking yet (Vismann 2012 p. 1200). According to (Lippok and Korth 2007 p. 117ff.), in deconstruction projects, materials and masses are still either calculated or estimated manually based on a site inspection. But, if there is suspicion of hazardous materials or contamination, various sampling methods via on-site or laboratory tests are recommended (Rommel et al. 1999). DIN 18459:2010-04 regulates the calculation of deconstruction projects and defines reference units for a large part of building elements and materials (see Table 2-6). Furthermore, DIN 18459:2010-04 defines additional services, that can be billed based e.g. on unexpected layers, materials or building elements that had not been detected previously in the building inspection. Also, it demonstrates that the calculation is both based on technical drawings (if existent) and the correct measurements onsite. This simple difference allows a lot of leeway in offering, bidding and calculation processes (DIN 18459:2010-04, 5.1.1). In practice, deconstruction masses are often roughly calculated via percentage of gross volume (BRI) e.g. 20% of gross volume (BRI) of a non-residential building or 20% ± 5% of another building type to calculate its concrete mass. The documentation is mainly paper-based and rather unstructured information including daily deconstruction records, agreements and minutes of meeting, correspondence, handover of technical documents, photographs, building inspection or evidence documentation e.g. regarding noise and vibration (Deutscher Abbruchverband e.V. 2015 p. 223).

The specific building history and the physical building properties with respect to year of construction, and related damages (e.g. due to war, fire or flood damages), construction type, retrofitting or extensions influence the building configuration. As data is often lacking (Raess et al. 2005; Volk et al. 2014) or conflicting with the current conditions onsite, indicators like gross floor area or gross volume are used to calculate elements and material masses. Top-down mass estimation is usually based on building type-based or building element-based indicators [t/m³] that refer to a buildings' gross volume (GV) and solid material densities of its masses (Toppel 2004 p. 143). It is often used for coarse calculations and disposal concepts.

Table 2-5: Relevant building documentation for deconstruction planning[19]

Documentation subject	Examples
Ownership, plot/parcel boundary	Land registry abstract, measurement plans
Approval documents	Building permit, site plan
Current state of execution and construction documents	Structural analysis calculations with position plans, execution plans of supporting structure and technical building equipment, detailing plans of interior fittings and facades, expert reports etc.
Strip plan of media lines/pipes	Water, waste water, power, gas, district heating, communications
Documentation of facility man-agement, retrofits, examinations, sampling	Retrofitting/renovation documents, remediation reports, changed use, other expert reports, measurements, warfare agents, hazardous materials
Changing exposures	Loads, groundwater level
Documentation of specific exposures	Damage by fire, water, mining, warfare
Documentation of neighboring buildings	Influence on neighboring buildings

Table 2-6 shows exemplary top-down material mass estimation factors. The values include building foundation up to 0.3 m and exclude technical equipment, glass, insulating materials and non-mineral partition walls. Although mass calculation is necessary for qualified bidding documents, these calculations and the resulting resource quantifications (quotation, cost estimation) are often performed under time pressure (Lippok and Korth 2007 p. 117ff.). And, a more detailed building auditing based on building elements, building materials and separation quality is associated with a high effort (Toppel 2004 p. 143).

[19] According to (Vismann 2012 p. 1198).

Table 2-6: Estimation factors of deconstruction material and mass [t/m³ GV] per residential building type and year of construction in literature[20]

<table>
<tr><th rowspan="2">Building type (construction type)</th><th colspan="3">Use</th><th colspan="3">Material and mass estimations in [t/m³ GV]</th></tr>
<tr><th>SFH</th><th>MFH</th><th>RA</th><th>Before 1918</th><th>1919-1948</th><th>1949-today</th></tr>
<tr><td>Building type I, II (solid construction, masonry and reinforced concrete/timber)</td><td>X</td><td>X</td><td>X</td><td>Concrete: 0.125
Brick: 0.214
Timber: 0.008
Metals: 0.007
Others: 0.003</td><td>Concrete: 0.116
Brick: 0.224
Timber: 0.009
Metals: 0.006
Others: 0.006</td><td>Concrete: 0.137
Brick: 0.206
Timber: 0.008
Metals: 0.003
Others: 0.018</td></tr>
<tr><td>Building type III (solid construction, reinforced concrete)</td><td>X</td><td>X</td><td>X</td><td colspan="3">Concrete: 0.369
Brick: 0.050
Timber: 0.002
Metals: 0.006
Others: 0.004</td></tr>
<tr><td>Building type IV (Frame construction, timber)</td><td>X</td><td>(X)</td><td>(X)</td><td colspan="3">Concrete: 0.036
Brick: 0.238
Timber: 0.028
Metals: 0.003
Others: 0.005</td></tr>
<tr><td>Building type IV (Frame construction, reinforced concrete)</td><td>(X)</td><td>X</td><td>X</td><td colspan="3">Concrete: 0.230 – 0.077
Brick:0.006 – 0.023
Timber: 0.004 – 0.009
Metals: 0.002 – 0.016
Others: 0.004 – 0.002</td></tr>
</table>

X: occurring SFH: Single family houses RA: Residential accommodation
(X): rarely occurring MFH: Multifamily houses

Mass calculation can be performed with or without building documentation. It is mostly based on a site inspection, corporate experience and reference values from literature (LfU 2001; Lippok and Korth 2007; Scholz 2002). Calculated masses and bill of quantities follow the hierarchy of building elements according to DIN 276-1:2008-12 (Schultmann

[20] (LfU 2001; Lippok and Korth 2007 p. 120). However, in other studies different concrete fractions of the listed construction types of (Buchert et al. 2004; Schiller and Deilmann 2010) are reported and a high variation can be identified (see also (Schiller and Deilmann 2010), p. 68, Abb.3-1).

1998) or a related hierarchy (Rommel et al. 1999). If building documentation like those mentioned in Table 2-5 is available, relevant building information can be extracted from it. But, often building documentation does not depict the as-built situation. If incomplete or no building documentation is available, mass calculation can be performed via standards depicting densities and weight of building elements (DIN EN 1991-1-1:2010; previously: DIN 1045-1:2008-08[21], DIN 1055-1:2002-06, DIN 1055-2:1976-02), relevant static tables (Verein Deutscher Eisenhüttenleute 1953; Vismann 2012 pp. 330–336) and costly onsite measurements of building elements. For architectural conservation of buildings, often historic standards from the year of construction are used and thus are increasingly documented and compiled[22].

Onsite measurements can be differentiated into capturing and imaging approaches for 3D reconstruction of element volumes as well as destructive and non-destructive testing of element materials and their qualities. As in mass calculation for deconstruction volume information is relevant, the following paragraphs depict possible capturing and imaging approaches and discusses their advantages and disadvantages.

[21] DIN 1045-1:2008-08 was used for calculation and dimensioning of reinforced concrete elements (walls, slabs and foundations/footings) until end of 2010, but since July 2012 the harmonized EUROCODE 2 (DIN EN 1992-1-1:2011-01 and DIN EN 1992-1-1/NA-2011-01) have to be applied. Nevertheless, DIN 1045-2, -3 and -4 are still in use.

[22] For historic standards for reinforced concrete buildings see e.g. (Fingerloos 2008) or for used concrete and steel qualities and configurations from 1920 until today (Vismann 2012 pp. 1206–1209).

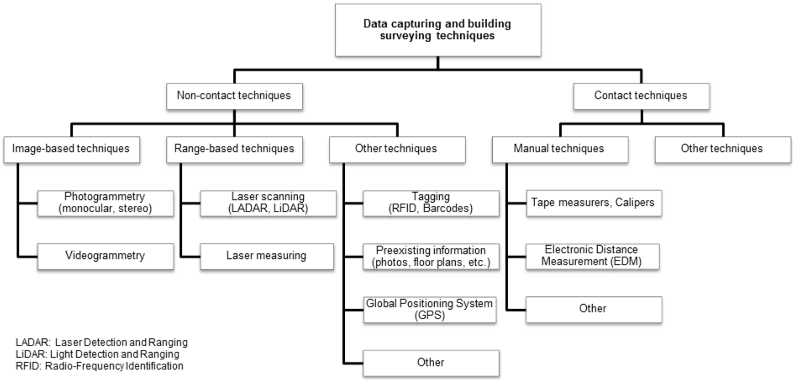

Figure 2-5: Systematic overview of data capturing and surveying techniques to gather existing buildings' information[23]

If building information is insufficient for required functionalities, techniques of data capturing[24] or survey are applied (Donath 2008) to audit buildings, and especially for new construction and retrofit purposes. In the following, an overview on current data and building information capturing techniques that are applied in building construction, maintenance, retrofitting and deconstruction contexts for the purpose of documentation and improvements of project planning and monitoring is given. Figure 2-5 shows non-contact techniques that can be further differentiated into image-based, range-based, combined or other techniques. Contact methods consist of manual or other techniques (Armesto et al. 2009; Markley et al. 2008; Remondino and El-Hakim 2006). Image- and range-based techniques extract mainly spatial, color and reflectivity information. In practice, semi-automated laser scanning with total stations is prevalent (Hajian and Becerik-Gerber 2010), although affected with disadvantages such as high equipment cost and

[23] (Arayici 2008; Bhatla et al. 2012 p. S. 119; Eastman et al. 2011; El-Omari and Moselhi 2011; Hajian and Becerik-Gerber 2009; Remondino and El-Hakim 2006; Vähä et al. 2013).

[24] Synonyms: data capture, data acquisition, data retrieval. However, building survey implies measurements from building components.

fragility as well as difficulties in scanning reflective, transparent and dark surfaces (Bhatla et al. 2012; Klein et al. 2012). Moreover, this technique needs further extensive data processing and modeling steps on conventional computers and current approaches have rather minor LoD (Brilakis et al. 2010; De Luca et al. 2006; Donath et al. 2010; Mill et al. 2013; Motawa and Almarshad 2013; Tang et al. 2010b p. S. 830; Tzedaki and Kamara 2013; Watson 2011; Xiong et al. 2013).

Manual techniques capture mostly spatial and other component-related information. Few approaches focus on other techniques like tagging (Costin et al. 2012; Jehle et al. 2011; Motamedi and Hammad 2009) or utilize preexisting building information (Domínguez et al. 2010; Donath et al. 2010; Liu et al. 2012) to gather additional information such as components' dimensions, materials, textures, functions, connections, positions or maintenance periods. RFID or barcode tags are rather installed in new buildings (Cheng and Ma 2011; Eastman et al. 2011; Li and Becerik-Gerber 2011), because in existing buildings tagging is limited by its installation effort (e.g. to retrofits), readability range and interoperability (Costin et al. 2012; Jehle et al. 2011; Motamedi and Hammad 2009).

Newer semi-automated, IT-based approaches perform building audits based on laser scanning or tagging (RFID, barcode) techniques, that support the generation of a digital building model and the automated derivation of bill of quantities and waste quantification (Chen and Li 2006). Many works consider deterministic auditing of existing buildings that is based on preexisting information like building element libraries, BIM or other documentation based on the assumption that the information is available and correct (Akbarnezhad et al. 2012, 2014; Cheng and Ma 2012; Raess et al. 2005; Schultmann 1998; Seemann 2003). If building information is gathered manually or (semi-)automatically during site inspections several techniques are available, such as tape measures, electronic distances measures or non-contact methods (see Figure 2-5). And, the required level of detail (LoD) determines all following steps from technique selection to model creation by its great influence on required data quality, data volume and processing effort.

Table 2-7: Characteristics of main data capturing techniques in the construction sector[25]

Decisive features	Data capturing techniques			
	Laser scanning	**Photo-gramme-try**	**RFID tagging**	**Barcode tagging**
Applicability in existing buildings	Yes	Yes	Limited	Limited
Cost	High	Medium	Medium	Low
Time	Medium	Fast	Fast	Fast
Spatial accuracy, Level of Detail	High	High	Medium	Medium
Influence of size and complexity of the scene	High	High	Low	Low
Influence of environmental conditions	High	High	Low	Low
Importability into BIM	Yes	Yes	No	No
Data volumes	High	Medium	Low	Low
Degree of automation	Medium	Medium	Low	Low
Operability	Low	Medium	Medium	Medium
Equipment portability	Low	High	High	High
Equipment durability and robustness	Medium	High	High	Medium

Table 2-7 summarizes the major data capturing techniques of laser scanning, photogrammetry and tagging that are relevant in research (Arayici 2008; Bhatla et al. 2012; Clemen and Gründig 2009; Dickinson et al. 2009; Golparvar-Fard et al. 2011; Klein et al. 2012; Tang et al. 2010b; Xiong et al. 2013) and their decisive features for technique selection. Main characteristics are cost, time, LoD and environmental conditions during data capture (e.g. light, weather, vegetation, concealments, clutter). Combinations of techniques are common and try to overcome drawbacks of individual capturing techniques (Chevrier et al. 2009;

[25] (Anil et al. 2013; Arayici 2008; Becker and Haala 2007; Bhatla et al. 2012; Costin et al. 2012; Dickinson et al. 2009; Golparvar-Fard et al. 2011; Jehle et al. 2011; Klein et al. 2012; Koenig et al. 2010; Mill et al. 2013; Motamedi and Hammad 2009; Remondino and El-Hakim 2006; Valero et al. 2012; Watson 2011; Zhu and Brilakis 2009).

El-Omari and Moselhi 2008; Frahm et al. 2010; Liu et al. 2012; Markley et al. 2008; Murphy et al. 2011; Valero et al. 2012). In practice, laser scanning is widely applied to measure infrastructures' and buildings' dimensions (Rottensteiner 2008; Tang et al. 2010a; Tang and Akinci 2012), and to record and update city surfaces (Golovinskiy et al. 2009).

Maintenance functionalities require a high LoD of components, the installed equipment, services and appliances (East et al. 2012). Therefore, tagging via RFID or barcodes is rather inadequate for application in maintenance in terms of spatial accuracy, LoD and degree of automation. Time and cost restrictions are major decisive features (Akbarnezhad et al. 2012) in deconstruction processes, but a related LoD and appropriate capturing technique is yet to be defined.

Recent research focuses on capturing mainly geometric data rather than semantic representations of buildings and feeding point cloud data into BIM software (Adan et al. 2011; Arayici 2008; Barazetti et al. 2010; Becerik-Gerber et al. 2011; Dai et al. 2011; Fathi and Brilakis 2011; Frahm et al. 2010; Furukawa et al. 2009; Klein et al. 2012; Mill et al. 2013; Ordóñez et al. 2010; Styliadis and Sechidis 2011; Yang et al. 2011). In the field of documenting historical buildings however, literature sources are numerous e.g. regarding the measurement and documentation of damages in digital building models (Tonn et al. 2013) or the auditing and modeling in historic building information models (HBIM) (Chevrier et al. 2009; Murphy et al. 2009, 2011; Penttilä et al. 2007; Yang et al. 2011). Furthermore, tools were developed to support the auditing of existing buildings (by photographs, notes, floorplans) and documentation of the actual condition per building elements according to DIN 276 as well as cost estimation for retrofitting measures in research (Donath 2008; Donath et al. 2010; Donath and Thurow 2007) and practice (SIRADOS 2015). However, the latter do not automatically model semantically enriched BIM or similar 3D building models, although recent works are improving (Thomson and Boehm 2015). Newer developments intensely research on process models for automated BIM modeling from captured data ('scan-to-BIM') and improvements in LoD (Tang et al. 2010b;

Tzedaki and Kamara 2013; Xiong et al. 2013) to enhance application in existing buildings.
In order to perform a comprehensive audit on existing buildings, the mentioned data capturing techniques might be combined with other methods of non-destructive testing to analyze materials and properties. Possible methods could include material- or texture-based recognition (Xiong et al. 2013) and structure recognition beyond surface through ground penetrating radars, radiography, magnetic particle inspection, sonars or electro-magnetic waves (Dai et al. 2011) or tags installed during retrofits. Future developments in automation of building auditing such as real-life automated building element and material recognition, as well as the connection and integration of element recognition and BIM are expected in the next years.
But, BIM is primarily (or almost exclusively) used in new construction yet. Further simulations in BIM software (e.g. in REVIT 4D) or BIM applications (e.g. Radiance) are still focused on representation of new building elements and quantity takeoff, scheduling or costing of new construction projects. However, recent trends show the shift of BIM use to retrofitting and deconstruction projects.
On building level, most approaches of FM, renovation, retrofitting and deconstruction research base on comprehensive and actual building documentation (Cheng and Ma 2011, 2012; Schultmann 1998) or if available, on actual Building Information Models (BIM) (Akbarnezhad et al. 2012, 2014; Penttilä et al. 2007) of the designated building. If actual building information/ a BIM exists, renovation, retrofitting and deconstructions processes can be planned and performed with smaller adjustments (Akbarnezhad et al. 2014). But more than 80% of European residential buildings were constructed before 1990 (Economidou et al. 2011) and often building documentation is poor and not reflecting actual conditions due to information loss during updates and buildings mainly do not have an actual BIM (Arayici 2008; Armesto et al. 2009; Attar et al. 2010; Dickinson et al. 2009). Exact building inventories and related data collection are essential for further data processing in the building sector

such as in life cycle analysis (Raess et al. 2005), maintenance or deconstruction planning (Schultmann 1998). If no actual building documentation is available, costly and mainly manual building auditing, documentation review and analyses of building properties (Donath et al. 2010; Penttilä et al. 2007) is necessary to provide a profound basis for process planning and cost estimating. Although many research approaches (Adan et al. 2011; Donath et al. 2010; Hajian and Becerik-Gerber 2010; Huber et al. 2011; Klein et al. 2012; Tang et al. 2010b; Valero et al. 2011; Xiong et al. 2013) try to overcome lacking or non-updated building documentation by capturing and processing (reverse engineering) of building information (Volk et al. 2014), but yet further research efforts are necessary in this field.

2.3.2 Deconstruction project planning

Yanagihara et al. formulate four areas with regard to project parameters that are relevant in deconstruction planning (Yanagihara et al. 2001 p. 194). These include experience data, facility information and work activities that are complemented by uncertainty and risk management (see Figure 2-6).

Usually, the gathered building or facility information in this project phase serves as a basis for bidding documents and the following deconstruction planning. Due to increasing recycling requirements, adequate and object specific techniques have to be applied that consider environmental aspects such as separation, material purity, separate collection of waste, potential contamination and adequate recycling or disposal options (DIN 18007:2000-05). In deconstruction planning, the deconstruction stages, as well as jobsite safety plans and on-site risk assessment according to BaustellV, contamination catalogue and recycling/disposal concepts have to be defined (Wangler et al. 2010). These plans have to include the cheapest safety/protective measures for the expected endangering in a project (Lippok and Korth 2007 p. 54). The here mentioned risk assessment includes mainly jobsite safety and safety/protective measures during deconstruction (Lippok and Korth 2007 p. 54), but often are not linked to project scheduling and disregards integrated risk management during project makespan.

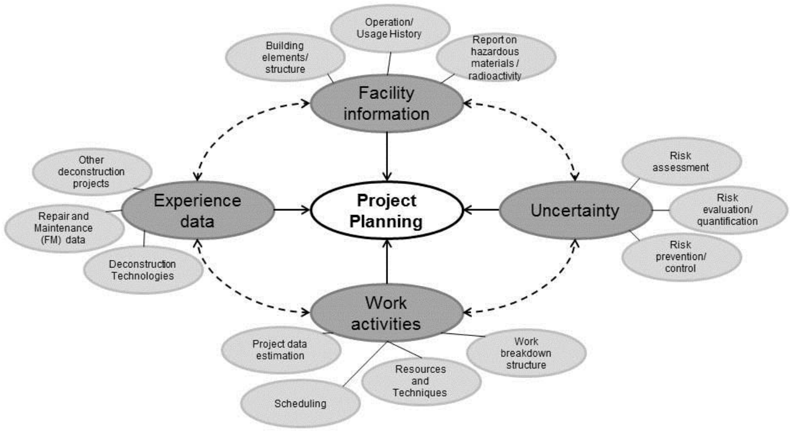

Figure 2-6: Overview on project management parameters for deconstruction projects[26]

Main (conflicting) objectives in the deconstruction of buildings are the minimal total project makespan and the total project cost (Schultmann 1998) subject to object-related constraints of time and space availability, sensitive buildings, constructions or equipment in the neighborhood (e.g. historic buildings, hospitals, production sites) or public transport (Lippok and Korth 2007 p. 352). Less relevant objectives in practice might be pollution control with respect to the avoidance of noise, dust or vibrations or the maximization of recycling rates. Thus, planning of deconstruction activities aim either at cost minimization under time constraints or at makespan reduction under budget constraints. Decisions in (de-)construction project planning include:

[26] Partly according to (Yanagihara et al. 2001 p. 194).

- numbers and capacities of resources (machines, staff),
- size of staff crews and their capabilities,
- hours and schedules of resources,
- rates of supply of materials (respective: logistics of materials and resources).

Activity-based methods are the method of choice in complex projects with little or no functional activity repetition (Kenley and Seppänen 2010 p. 49). Mainly applied in method in construction projects is the critical path method (CPM or PERT, see also section 3.3), but their schedules are prepared and ignored as well as targets are not met and durations are exceeded (Kenley and Seppänen 2010 p. 45). To control projects, many indicators can be applied. In deconstruction projects, indicators like gross volume (enclosed space), gross floor area, total project makespan, total project cost or number of employees at the project are applied.
Today, mainly experienced staff coordinates deconstruction scheduling and capacity planning. In practice, about 20% of additional time is calculated to buffer machine breakdowns, staff illnesses or unexpected events such as the unanticipated finding of hazardous materials or building elements[27]. Sometimes, more specialized enterprise resource planning (ERP) systems such as 'BauSU'[28] or 'EMOS'[29] are applied for corporate resource planning. Main focus of the applied ERP systems are accounting and in-house resource management, less considered are the specific activity scheduling in projects and consideration of uncertainties in deconstruction projects. Project management solutions (e.g. 'ProbauS'[30]) allow the management of projects and resources, but also neglect the consideration of uncertainties in project planning and execution. Generated materials and wastes are delivered to the legally re-

[27] This statement was documented in a project meeting with practitioners of research project ResourceApp (BMBF) on 28. April 2014 in Peine/Braunschweig.
[28] http://www.bausu.de/
[29] http://www.emos-system.de/start.html
[30] http://www.probau-s.de/

quired waste tracking (eANV) for hazardous wastes, often via electronic systems such as 'Zedal/Krk/G-Soft e-Form'[31].

Furthermore, in the Netherlands the freely available Slim Slopen Tool (Smart Demolition Tool)[32] was developed to take the level of sustainability in the decision making phase into account for a specific demolition scenario (equipment, transport, materials and products). Commissioners and executioners of demolition works can use the instrument for practical and quick quantitative assessment of the environmental benefits of 'sustainable' demolition (measured in LCA categories kg CO_2 equivalents (climate change) and kg NO_x (indicator of air pollution and smog formation)) compared to traditional demolition (EU Commission 2008).

Thus, deconstruction planning is a complex planning task that can be supported by operative project management methods for process optimization, controlling and decision making. However, currently applied methods do rather not support multi-project or multi-mode optimization or robust resource planning under uncertainty (see also section 3.4 for a comprehensive overview on deconstruction project planning methods in literature).

2.3.3 Excursus: Building information capture and modeling in construction

In construction projects however, semantic building (information) models (BIM) and their applications[33] are increasingly used for construction project management and respective activity scheduling, progress tracking and deviation analysis, cost calculation, controlling, documentation etc. Building (Construction) Information Model (BIM) is defined by international standard ISO 29481-1:2010-05 as the "shared digital representation of physical and functional characteristics of any built

[31] http://www.zedal.de/
[32] http://www.rotterdam.nl/slim_slopen, http://www.ivam.uva.nl, (EU Commission 2008).
[33] For further information on building information models and their technical, informational and organizational issues see e.g. (Volk et al. 2014).

object […] which forms a reliable basis for decisions" (ISO Standard 2010). BIMs originate from product models (Borrmann and Rank 2009; Cerovsek 2011) that are widely applied in the petrochemical, automotive or shipbuilding industry (Eastman et al. 2011; Wong and Yang 2010). BIM represents real buildings virtually over the whole lifecycle (LC) as semantically enriched, consistent, digital building models (Eastman et al. 2011; Tang et al. 2010b; Watson 2011 p. S. 573f.). BIM is realized with object-oriented software and consists of parametric objects representing building components (Cerovsek 2011; Lee et al. 2006; Nicolle and Cruz 2011). Objects may have geometric or non-geometric attributes with functional, semantic or topologic information (Eastman et al. 2011; Wong and Yang 2010). For example, functional attributes can be installation durations or costs, semantic information store e.g. connectivity, aggregation, containment or intersection information with other building elements and topologic attributes provide e.g. information about building elements' locations, adjacency, co-planarity or perpendicularity. As BIM is a means to manage accurate building information over the whole LC (Liu et al. 2012), it is adequate to support data of maintenance and deconstruction processes (Akbarnezhad et al. 2012; Cheng and Ma 2012; Eastman et al. 2011). Moreover, all stakeholders in different phases can be coordinated over the facility lifecycle, and thus the process productivity can be improved.

Due to numerous design, engineering, construction, maintenance and deconstruction services during building LC, potential applications and required functionalities of BIM in buildings and infrastructures are manifold. Table 2-8 displays major examples of inherent and expert BIM functionalities applied in practice and examined in research. Currently, research rather focuses on expert functionalities for new buildings, such as energy and carbon reduction analyses, construction progress tracking (matching captured data with preexisting BIM), deviation analyses (quality control, defect detection) and jobsite safety. According to BIM's original application in new construction, applied functionalities concentrate on design and visualization, procurement, manufacturing, construction management and coordination rather than on commissioning, facility management or deconstruction (Liu et al. 2011). Non-proprietary BIM standard format for data exchange is IFC defined in ISO/PAS 16739:2005.

Table 2-8: Examples for major applied or developing BIM functionalities for existing buildings[34]

Functionality	**Research**	**Practice**
Clash detection, Spatial program validation, BIM quality assessment	(Eastman et al. 2011; Tang et al. 2011)	(Eastman et al. 2011; NIBS and buildingSMARTalliance 2012; Solibri 2013; *Vico Office Suite - A Construction-Oriented 5D BIM Environment* 2013)*
Construction progress tracking	(Bhatla et al. 2012; Bosche 2010; Bosche and Haas 2008; Eastman et al. 2011; El-Omari and Moselhi 2008, 2011; Golparvar-Fard et al. 2011; Hajian and Becerik-Gerber 2009; Makhmalbaf et al. 2010; Tang et al. 2010a; Turkan et al. 2012; Weldu and Knapp 2012; Yeh et al. 2012)	-
Cost calculation or Cash flow modeling (5D)**	(Campbell 2007; Cheung et al. 2012; Eastman et al. 2011; Gu and London 2010; Hartmann et al. 2012; Hirsch 2012; Shen and Issa 2010)	(Autodesk 2013a; NIBS and buildingSMARTalliance 2012; RIB 2012; *Vico Office Suite - A Construction-Oriented 5D BIM Environment* 2013; VICO Software 2012)
Daylight simulation	(Welle et al. 2012)	(Autodesk Revit 2013; EETD 2013)
Deconstruction, Rubble management	(Akbarnezhad et al. 2012, 2014; Cheng and Ma 2012)	-
Deviation analysis, Quality control, Defect detection	(Akinci et al. 2006; Anil et al. 2011, 2013; Boukamp and Akinci 2007; Hajian and Becerik-Gerber 2009; Huber et al. 2011; Liu et al. 2012; Mill et al. 2013; Tang and Akinci 2012; Yue et al. 2006)	-

[34] (Volk et al. 2014).

Documentation, Data management and Visualization	(Akcamete et al. 2010; Asen et al. 2012; Eastman et al. 2011; Gursel et al. 2009; Murphy et al. 2009; Nicolle and Cruz 2011; Weldu and Knapp 2012; Yeh et al. 2012)	(Asite 2013; Bentley 2013a; Eastman et al. 2011; GitHub 2013)
Energy/Thermal analysis and control, Carbon foot printing	(Bazjanac 2008; Cho et al. 2010; Eastman et al. 2011; Hirsch 2012; Kim et al. 2012; Moon and Choi 2012; Welle et al. 2011)	(Autodesk 2011, 2013b; EERE 2013; EnergyPlus 2013; NIBS and build-ingSMARTalliance 2012)
Localization of building components, Indoor navigation	(Akcamete et al. 2010; Becerik-Gerber et al. 2012; Cheng and Ma 2011; Costin et al. 2012; Jehle et al. 2011; Li and Becerik-Gerber 2012)	-
Life cycle assessment (LCA), Sustainability	(Azhar et al. 2011; Becerik-Gerber et al. 2012; Bynum et al. 2012; Cho et al. 2010; Isikdag et al. 2013; Wang et al. 2011; Wassouf et al. 2006; Wong and Yang 2010)	(Autodesk 2011)
Monitoring, Perfor-mance measurement (through sensors)	(Dibley et al. 2012; Gursel et al. 2009; Maile et al. 2010a; b)	(Autodesk 2013c)
Operations and Maintenance (O&M), Facility management (FM)	(Akcamete et al. 2010; Becerik-Gerber et al. 2012; British Institute of Facilities Management 2012; Campbell 2007; East 2012; East et al. 2012; East and Carrasquillo-Mangual 2013; Eastman et al. 2011; Hajian and Becerik-Gerber 2009; Hu et al. 2012; Lucas et al. 2013; Motawa and Almarshad 2013; Nicolle and Cruz 2011; Turkaslan-Bulbul and Akin 2006)	(Amtech Group 2015; Asite 2013; AssetWorks 2013; Autodesk 2013d; Bentley 2013b; Ecodomus 2013; FAMIS 2013; Four Rivers Software Systems 2013; IBM 2013; Nemetschek 2013a; Sabol 2008; TMAsystems 2013)
Quantity takeoff (3D)	(Eastman et al. 2011)	(Autodesk 2013a; NIBS and buildingSMARTalliance 2012; *Vico Office Suite - A Construction-Oriented 5D BIM Environment* 2013)*
Retrofit /Renovation planning and execu-tion	(Becerik-Gerber et al. 2012; Donath et al. 2010; Donath and Thurow 2007; Penttilä et al. 2007; Yee et al. 2013)	-
Risk scenario plan-ning	(Gu and London 2010; Hartmann et al. 2012)	-
Safety, Jobsite safety, Emergency Man-agement	(Akinci and Anumba 2008; Ben-jaoran and Sdhabhon 2010; Cox and Terry 2008; Lin et al. 2011; Shino 2013; Teizer et al. 2010; Zhang et al.	-

	2010, 2012; Zhang and Hu 2011; Zhou et al. 2012)	
Scheduling (4D)	(Campbell 2007; Eastman et al. 2011; Gu and London 2010)	(*Vico Office Suite - A Construction-Oriented 5D BIM Environment* 2013)
Space Management	(Becerik-Gerber et al. 2012; Kim 2013; Kim et al. 2012)	-
Structural analysis	(Lee et al. 2012; Sacks and Barak 2008; Zhang and Hu 2011)	(Bentley 2013c; *Bentley PowerRebar* 2013; Liberty Industrial 2012; Nemetschek 2013b)*
Subcontractor and supplier integration, prefabrication (e.g. of steel, precast components, fenestration, glass fabrication)	(Campbell 2007; Eastman et al. 2011)	(Eastman et al. 2011)
*: available in every major BIM software (Eastman et al. 2011), **: often country-specific		

Unfortunately, there are no statistics on the use of BIM in the construction, FM and deconstruction industry (Liebich et al. 2011), but it can be assumed that mainly insular solutions are applied from architectural and engineering experts. In Europe, more than 80% of residential buildings are built before 1990 (Economidou et al. 2011) and do mainly not have a building documentation in BIM format (Arayici 2008; Armesto et al. 2009; Attar et al. 2010; Dickinson et al. 2009). Therefore, if implemented in practice, costly and mainly manual reverse engineering processes (‘points-to-BIM’, ‘scan-to-BIM’) might help recapturing building information (Klein et al. 2012; Valero et al. 2011).

According to recent surveys, BIM is suitable for larger and more complex buildings and applied by the respondents of recent surveys in commercial, residential, educational, healthcare and many other building types (Becerik-Gerber and Rice 2010; RICS 2013). But since less than 10% of the respondents are facility managers, owners or deconstructors, these trends do not reflect current the use of BIM in existing buildings (Becerik-Gerber and Rice 2010; RICS 2013). Potential benefits of using BIM in FM seem to be significant (Akcamete et al. 2010; Arayici 2008;

Becerik-Gerber et al. 2012), e.g. as valuable 'as-built' (heritage) documentation (Eastman et al. 2011), maintenance of warranty and service information (Arayici 2008; Becerik-Gerber et al. 2012; Singh et al. 2011), quality control (Akinci et al. 2006; Boukamp and Akinci 2007), assessment and monitoring (Arayici 2008; Becerik-Gerber et al. 2012; Eastman et al. 2011), energy and space management (Becerik-Gerber et al. 2012; Cho et al. 2010), emergency management (Arayici 2008) or retrofit planning (Arayici 2008; Mill et al. 2013). Decontamination or deconstruction processes could also benefit from structured as-built building information to reduce project planning and decision making errors and financial risk, e.g. through deconstruction scheduling and sequencing, cost calculation, rubble management, optimization of deconstruction progress tracking or data management. Moreover, building documentation might be improved and complemented through available, comprehensive databases of building elements of their manufacturers (e.g. enriched with handling instructions, warranty information etc.).

Other building models used for project management are based on tags such as RFID or barcodes, allowing the localization of building elements and saving building information in a decentralized manner. Examples of tag application is mainly found in models with scopes of logistics (Chen and Li 2006 p. 83ff.; Cheng and Ma 2011; Costin et al. 2012; Jehle et al. 2011; Li et al. 2005; Ruan and Hu 2011) or information flow (Cheng and Chang 2011; Jehle et al. 2011). But as these systems only save building element-related information, they are less adequate for operative project planning and management activities. Other approaches link BIM and GIS systems to visually survey construction supply chain management (Irizarry et al. 2013) or connect BIM, RFID and electronic online transaction platforms (Cheng and Chang 2011).

Before broadly using these innovative approaches in the German C&D industry, legal conditions like contract proposals, liabilities, technical and service specifications and HOAI pricings need to be adapted (Egger et al. 2013; Liebich et al. 2011). Furthermore, technical standards like DIN 276 need to be linked with BIM levels of detail (Liebich et al. 2011). But recent publications on BIM libraries (e.g. Germany: Nationale Bibliothek für BIM-Objekte - INS 1265, Great Britain: NBS National BIM Library[35], Australia: NATSPEC BIM, or others mentioned in (AEC Magazine 2014)) and of DIN SPEC 41900 show progress in this matter.

2.3.4 Preparation of deconstruction: clearance and decontamination

Previous to the deconstruction of a building, preparatory measures have to be performed to successfully deconstruct a building or infrastructure. Current practice often is a partly deconstruction especially of hazardous and valuable materials (Martens 2011 p. 328f.). Thus, main two aspects are the decontamination and the site clearance (Lippok and Korth 2007 pp. 18–21) that are described in the following.

First of all, the building is decontaminated if hazardous materials or building elements are inherent in the building. The client or the responsible design engineer has the obligation to communicate potential hazardous materials and contaminations in the bidding process, e.g. in the call for bids or the description of services. Generally, before deconstructing a building, all suspicions on hazardous materials and elements have to be evaluated by an expert and documented. If contaminations were found, their proper dismantling, removal and deposition has to be secured. This especially applies for asbestos, asbestos-containing materials and synthetic mineral fibers (KMF) (TRGS 519, 521). VDI 6202-1:2013-10 (VDI 2013) describes in detail the necessary requirements and process steps of remediation processes in buildings. Also, classical hazardous components such as batteries, capacitors, fire detectors or fluorescent lamps are usually removed in this step (Martens 2011 p. 328f.). Since April 2010, hazardous wastes have to be registered and tracked electronically via the electronic waste tracking system ‘eANV’ in Germany.

[35] http://www.nationalbimlibrary.com/find-bim-objects (accessed: 19.05.2016)

Then, the building site is cleared from all interior and exterior fittings. According to (Lippok and Korth 2007 p. 23), site clearance is further divided into clearing out and gutting. Clearing out describes the removal of mobile equipment, such as furnishing, carpets, curtains or blinds, laboratory or kitchen elements. Gutting refers to the dismantling of all attached or incorporated (technical) equipment that does not influence the structural safety of the building. Examples are windows, doors, stoves, piping, covering elements, suspended ceilings or non-bearing interior walls. Also, before deconstruction the draining of oils, cooling mediums or gases as well as the removal of valuable materials or elements such as lead-acid batteries, transformers, electric motors, aluminum and magnesium components, plastic components, copper wiring harnesses is done (Martens 2011 p. 328f.).
The efforts necessary for site clearance strongly depend on the condition of the building that will be deconstructed. These activities require manual labor, containers for respectively material classification (according to EWC or other classification demanded by the recycling or disposal facility) and can be performed by several teams in parallel.

2.3.5 Deconstruction and deconstruction techniques

Deconstruction activities can include dismantling, sorting, crushing, breaking, milling, storing, loading and transporting building elements and materials. In the following sections, the kind of deconstruction activities, their precedence relations in a deconstruction project and suitable techniques to perform the activities are shown.

2.3.5.1 Deconstruction degree

The planned deconstruction activities executed in this stage mainly depend on the previously defined final status of the site and the desired material fractions and recycling qualities. In literature, this is depicted as deconstruction degree and separated into several steps (see Figure 2-7). Despite the often postulated material-oriented (selective) deconstruction of a building (Schiller and Deilmann 2010), deconstruction activities precede and follow mainly the reverse order of the construction process of a building (Lippok and Korth 2007 p. 358; Schultmann 1998). Preceding activities in the deconstruction schedule are the preparatory activities of site clearance and decontamination (Dehoust et al. 2008 p. 52; Lippok and Korth 2007 pp. 18–21) followed by an adequate material separation.

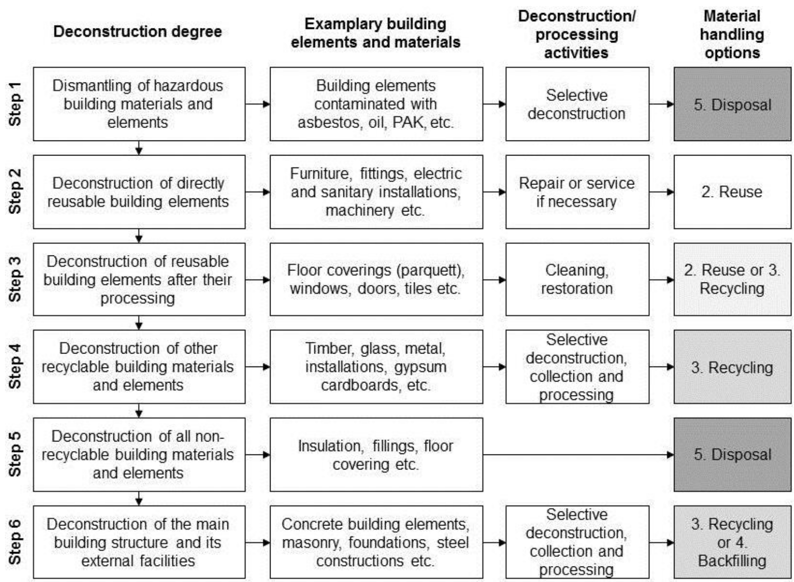

Figure 2-7: Deconstruction degrees, exemplary building elements and materials, resulting deconstruction and processing activities and material handling options (no.)[36]

Deconstruction activities can be performed via different techniques (Lippok and Korth 2007), depending on the object (building, infrastructure) that will be deconstructed, the defined deconstruction stages, the

[36] According to KrWG and (BDE 1996 p. 14).

available resources (staff, machinery and trucks, container, etc.), the required material (separation) quality, the recycling and disposal concept as well as the safety and environmental protection measures.

2.3.5.2 Activity precedence in building deconstruction and recycling/disposal

Prerequisite for the demolition of multi-story residential and societal buildings is the gutting and removal of contamination (Lippok and Korth 2007 p. 352 and chapter 3.3) according to the legal requirements (see section 2.2). After decontamination and gutting of a building, building/construction stability is key in the determination of deconstruction activities and activity groups and their precedence relations of the deconstruction activities especially of vertical building elements (Lippok and Korth 2007 p. 352). Thus, for example first non-bearing walls, then interior walls and finally exterior walls are deconstructed (Lippok and Korth 2007 p. 354). Component connections are loosened starting from inside, necessary auxiliary constructions and intermediate storage of generated materials at the construction site should be minimized (Lippok and Korth 2007 p. 354).

From the deconstruction degrees of exemplary building elements and materials (Figure 2-7) and practical considerations, the predefined deconstruction activity precedence relations result (Figure 2-8) and imply the deconstruction project structure. Generally, the building is decontaminated first, which means that all hazardous building elements and hazardous materials are removed. Then, a building is gutted, which includes the removal of furniture, fittings, technical equipment and installations, windows and doors. Then, the structure is demolished. Technical equipment, interior and exterior fittings are mainly not restricted by precedence constraints, while deconstruction activities related to the supporting structure of a building follow a strict order. Generally, technical equipment and fittings can be gutted in parallel before the building structure is torn down, leading to a dichotomy of parallel and sequential project activities. This is followed by the decon-

struction of the main structural building elements. Some precedence relations, that naturally follow each other can also be denominated as “disassembly chains” (similar to critical chains of (Goldratt 1997)), especially when they constitute the critical path (e.g. the deconstruction of the main structure).
The described precedence follows (Deutscher Abbruchverband e.V. 2015; LfU 2001; Schultmann 1998 p. 174,188) and VDI 6202-1:2012-06. In the following case studies, these principal precedence relations are underlying the precedence considerations and matrices in chapter 5.

2.3.5.3 Deconstruction techniques and suitability

Many techniques are available to deconstruct building elements. Core deconstruction techniques can be differentiated into dismantling (tearing, tapping, bashing in etc. and blasting) and separation techniques (sawing, drilling, hydraulic or thermic techniques) (Seemann 2003 pp. 42–49). Depending on the building type and the framework conditions, some techniques are more adequate for specific deconstruction activities than others. A comprehensive overview and detailed descriptions of the specific techniques, their advantages and restrictions can be found in (Deutscher Abbruchverband e.V. 2015; Toppel 2004 pp. 77–94). The selection of the most adequate deconstruction technique mainly depends on the vertical construction and its building element material, the available technical equipment of the respective deconstruction company and the experience already gained (Lippok and Korth 2007 p. 352). The use of certain deconstruction techniques greatly depends on their suitability to elements and materials (see Appendix of DIN 18007:2000-05), but also on operation height above ground level, building element thicknesses and site conditions. The following Table 2-9 shows the most common deconstruction techniques and their suitability depending on building construction, building elements and materials.

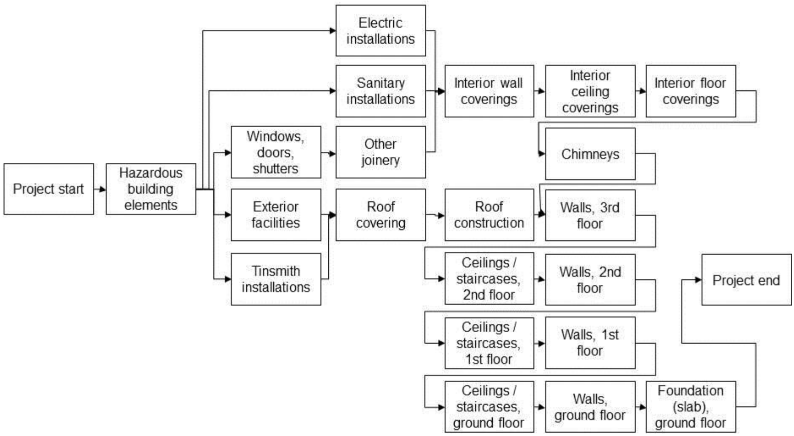

Figure 2-8: Exemplary deconstruction activity precedence in a three-storey building deconstruction project[37]

The mostly used technique up to a height of 40 m above ground level is a hydraulic excavator with different (long front) booms and accessory equipment and attachments like combi-cutters, demolition hammers, steel scissors and demolition and sorting grabs (Lippok and Korth 2007 p. 352). In cases with low space availability, hoisting devices are often applied (Lippok and Korth 2007 p. 352). Due to differing building and construction types, the selection of the most advantageous deconstruction method can generally not be determined by building type, but mostly contains a combination of methods (Lippok and Korth 2007 p. 352). Depending on the dominating material and the selected deconstruction technique, downstream activities like shredding, sorting and loading require more or less time and effort. For example, shredding of masonry is rather easy while sorting of reinforced concrete is relatively costly (Lippok and Korth 2007 p. 352).

[37] According to (Schultmann 1998 p. 188).

Table 2-9: Deconstruction techniques and their applicability on building construction types, building elements and element materials[38]

Applicability and effects of deconstruction techniques	Construction									Building element								Material											
Techniques	low rise buildings and halls	multi-story skeleton structures	multi-story wall constructions	compact buildings	tower-like structures / chimneys / pylons	bridges	silos and containers	shell construction	traffic infrastructures	ceilings / floors	arches	roofs	joists / beam / trusses	pillars	walls	foundations / foundation bodies	machines / plant components	timber	masonry	asphaltic concrete	non-reinforced concrete	reinforced concrete	steel	high-alloy steel and casting	nonferrous metals	insulations and finishings	plastics	asbestos	synthetic mineral fibre
grabbing, gripping	●	○	●		○							○	○		●		○	●	●		○ 1)	○ 1)	○ 1)			●	●		○
hammering	●	●	●	○	●	○	●	●	●	●	●	●	●	●	●	○	○		●	●	●	●	○	○					
pressing	●	○	●				○					○		○	●			●	●				○						
pulling	●	●	○		○							○		●	○			●	●		○	● 1)	● 1)						
tearing									●	●						○			●	●	●	○							
chiseling	○	○	○	●		●	○	○	○	●	○	○	●	●	●	●			●	○	●	●		○					
pressure cutting, pulverizing	●	●	●		●	○	●	○	○	○		○	●	●	●				●	○	●	●							
shear cutting	●	●	○		●	●	●	●				○	●	●	○		●	○					●				○		
splitting through compression	-- independent of construction --									●	●		○	○	○	●			○		●	○							
splitting through swell pressing	-- independent of construction --									●	●		○	○	○	●			○		●	○							
disassembly / deconstruction	●	○	○		○	○	○		○			○	○	○	○		●	●				○	●	●	●	●	●	●	●
loosening blasting	-- independent of construction ---									●	●		●	●	○	●			○		●	●		○					
splitting through blasting	-- independent of construction ---										○				○	○			○		●	●	●						
turn-over through blasting		●	●		●		●			-- independendet of element --								○	●		●	●	●						
collapsing through blasting	○	●	●		○	○		●		-- independendet of element --									●		●	●	○						
putting down through blasting		●	●				●	○		-- independendet of element --								○	●		●	●	○						
core-sampling	-- independent of construction --									●	●		●	●	●	●			●	○	●	●							
solid drilling	--------------------------- only part of other techniques ---------------------------																												
wall sawing	-- independent of construction --									●	○	●	●	●	●	○			●		●	●							
floor sawing	-- independent of construction --									●		○	○			○			●	●	●	●							
wire sawing	-- independent of construction --									●	●	○	●	●	●	●			●		●	●							
chain sawing	-- independent of construction --														●			●	●		●	●							
autogenes flame cutting	-- independent of construction --												●	●	○		●						●	○					
plasma cutting	-- independent of construction --												○	○	○		●						○	● 2)	●				
thermal lance flame cutting	-- independent of construction --									○	○		○	○	○		●					○	●	●	●				
mineral-powder flame cutting	-- independent of construction --									○	○		○	○	○		●						●	●	●				
high-pressure water cutting	-- independent of construction --									●		○			○		●		○		○	○	●	●	●		○	○	
milling	-- independent of construction --									●	○	○	○	○	○	○			●	●	●	○							
grinding	-- independent of construction --									●	○	○	○	○	○	○	○		●	●	●	○	○	○	○		○		
high-pressure water jetting	-- independent of construction --									●		○			○		●		○		○	○	●	●	●		○		

○ = suitable
● = particularly suitable

1) has to be removed from the compound / composite material through other techniques if necessary
2) does not apply for casting materials
x = emissions have to be considered if necessary

2.3.5.4 Crushing, sorting and processing techniques

As this research contribution considers buildings, generated materials and debris mainly consist of gravel, sand, concrete, stones, bricks, ceramics, gypsum/plaster, and mortar. Moreover, also metals, plastics, timber, paper or glass might be included (Dehoust et al. 2008 p. 52).

[38] According to DIN 18007:2000-05, Appendix A.

Other sorting and processing techniques related to excavated soil, road scarification or track ballast are not considered here[39].

Depending on the required RC material quality, several processing steps[40] in mobile or stationary aggregates can be applied (Seemann 2003 p. 53). After the deconstruction of building elements and materials, the debris masses are sorted, shredded, processed and recycled onsite or conditioned for transportation to recycling, reprocessing or disposal facilities. The extent of sorting process steps after deconstruction mainly depends on the space availability onsite. Manual sorting by hand separates hampering particles up to five kg, while "manual" sorting with hydraulic excavators and sorting grab includes heavier elements (Seemann 2003 p. 51). This kind of sorting is often performed onsite to separate timber and plastic particles.

Sorting and reprocessing facilities crush (via jaw and impact crusher), classify (via sieving), mill, wash and sort deconstruction debris into main waste fractions of minerals, timber, steel, plastics and other materials offsite. Sorting out of hampering materials and building elements like metals, plastics, timber, paper, or glass is done in these aggregates by air classification, magnetic separation, water separation or manually (Dehoust et al. 2008 p. 52). However, air classification and magnetic separation automated sorting of hampering substances is seldom applied in practice (Seemann 2003 p. 53). While mobile facilities are smaller and operate onsite, stationary offsite facilities are larger and include further sorting steps. In contrast to stationary facilities, semi-mobile and mobile aggregates do not sort materials (Dehoust et al. 2008 p. 52). Both mobile and stationary facilities recycle the generated materials, but

[39] For further details on waste classification and material qualities see (Dehoust et al. 2008 pp. 45–53).

[40] A detailed description of the sorting techniques and recycling and disposal options is given in (Dehoust et al. 2008 pp. 45–53; Lippok and Korth 2007; Seemann 2003 pp. 14-69). Advantages and restrictions of different sorting and processing aggregates can be found in (Seemann 2003 p. 56).

differ regarding their mobility, capacities, their shred grain size, and their sorting quality and technique (Seemann 2003 p. 54).

2.3.6 Reuse, recycling and disposal

The main RC material fractions generated in buildings are concrete, brick, steel and other metals. Reuse and recycling of material and elements in buildings and infrastructures are subject to numerous legal requirements (see section 2.2). At least, requirements for new/raw construction materials apply with respect to definition of material type, grain size, density, frost resistance or compressive strength. Often, requirements of RC materials are either stricter than for raw materials or not defined at all which both hinders RC material use.

Major material quality classification schemes of debris material qualities and related safety thresholds are LAGA for debris, TL Min-StB 2004 and RAL-GZ 501/1 for road works and AltholzV for timber. Most important standard for the use of recycled, secondary concrete (RC concrete) is DIN 4226-100:2002-02 (and withdrawn DIN EN 12620:2013-07) uniformly regulating the use of concrete aggregates in buildings and infrastructure and their environmental impact assessment. Often, recycling and disposal facilities have additional, regionally varying material classification schemes.

Reuse or recycling of material or building elements are possible either directly onsite in new construction or fillings e.g. in landscaping or increased ground level or, indirectly through online trading at materials and building elements exchange platforms[41]. Due to the multitude of building materials and elements, there are numerous recycling options and application areas of RC materials (see Table 2-10). A detailed description of the recycling and disposal options is given in (Dehoust et al. 2008 pp. 45–53; Lippok and Korth 2007; Seemann 2003 pp. 14-69).

[41] These are so-called ‘Baustoff-/ Bauteilbörsen’ e.g. in Berlin-Brandenburg, Bremen, Gronau or Germany-wide (“Bauteilbörse Berlin-Brandenburg” 2003, “Bauteilbörse Bremen”, “Bauteilbörse Gronau” 1995, “bauteilnetz Deutschland” 2006).

Following the circular economy thinking, the application of RC materials in their original purpose is pursued. However, the regulations and common practices are often not defined yet.

Table 2-10: Application areas of mineral RC material[42]

Road/earth work and civil engineering	Concrete construction	Landscaping
• dam and filling materials (e.g. noise barriers, back-filling of pits, trenches or mines) • soil improvement and soil stabilization • frost protection layers • unbound or hydraulically bound, asphalt or paving base layers • aggregate in concrete road pavement	• aggregates in concrete structures, reinforced concrete and mortar • cleanliness layers under foundations • concrete in road works, garden and landscaping • cement screed	• substrate in roofing • lawn substrate • parking deck substrate • tree substrate in urban areas • gravel turf (e.g. in emergency lanes/areas)

For example, RC ready-mix concrete can be differentiated into two major types: (1) concrete with fractions (> 90% mass) of crushed concrete or primary aggregate (type I) and (2) concrete with fractions of crushed concrete or primary aggregate (> 70% mass) and crushed masonry (< 30% mass) (type II) (e.g. brick, lime sand brick, etc.)[43]. RC concrete type I can attain the same qualities and properties as primary concrete, but RC concrete type II often results in other properties such as increased water retention capacity, grain size, grain density or strength that have to be tested and documented with additional, expensive

[42] According to (ARGE KWTB 2001, 2003; Dehoust et al. 2008 p. 28, 56ff.; Lippok and Korth 2007 p. 431ff.).

[43] In Switzerland, a pioneer in concrete recycling, sia-Merkblatt 2030 regulates the use of RC concrete (type I = RC-C, type II = RC-M). In contrast to Germany, RC concrete use is obligatory and use of primary concrete requires permission since a decade.

testing methods.[44] Thus, RC concrete type II is not applied in practice yet, except for pilot project in Zurich using more than 30% (mass) in special uses such as inner walls. According to DafStb regulation, concrete according to DIN EN 206-1 and DIN EN 1045-2 [Fachbericht 100] with recycled aggregates according to DIN EN 12620:2010, RC concrete type I with compressive strength up to C 30/37 and usual exposition classes can be applied in buildings. Furthermore, the annually updated "Bauregelliste" and "List of technical construction regulations" (LTB) regulate the applicability of building products and elements according to the respective Landesbauordnung. For further information on mineral RC material quality and testing see (Dehoust et al. 2008 p. 97ff.; Susset and Leuchs 2011). For an overview on RC material regulations see (BRB 2006; Lippok and Korth 2007 pp. 431–447) and on RC material acceptance and use see (Knappe et al. 2012).

Used timber can be classified into untreated timber, painted, varnished and coated timber with and without halogenated organic coatings and timber treated with preservatives. Potential recycling paths are chipboards, use in composting facilities, barn litter or in landscaping as well as energetic use. However, these uses are not yet regulated. For used PVC there is no classification scheme, but it can be returned at few facilities where the RC material is processed to floor coverings, roof coverings, window frames or piping (Lippok and Korth 2007 p. 444f.). If hampering substances like gypsum are separated, often they are recycled and re-included into the gypsum industry or else deposited if possible. Hazardous materials are disposed, often after further processing like vitrification or encapsulation to hinder diffusion into the environment.

[44] Extensive regulation on testing methods and their minimum test frequencies in this area can be found in DIN 4226-100:2002-02 (labelling, water retention), DIN EN 932-1, DIN EN 933-1:2006-01 (grain size distribution), DIN EN 933-4:2008-06 (grain form), DIN EN 12390-3:2002-04, DIN EN 1097-6:2005-12 (grain density), DIN EN 1744-1/5/6, DIN EN 1367 (concrete compressive strength), DIN EN 12390-5:2001-02 (flexural strength), DIN 1048-5:1991-06 (modulus of elasticity).

2.3.7 Deconstruction project controlling

In practice, effects of uncertainties in deconstruction projects e.g. deviation of material masses (+/-10% of the masses in contractual agreements), changes in planning or additional services can be accounted as supplementary claims (see also (§ 2, No. 3, Sec. 2 VOB/B)).
Controlling of deconstruction projects status is done almost on daily basis, while usual status updates in construction projects (managed under lean construction principles) are fixed, weekly periods (Ballard and Howell 2003; Issa 2013 p. 699; Seppänen et al. 2010). Almost daily updates allow short-term project and resource planning and resource shifting (between projects) to keep contractual agreements and to avoid contractual penalties. The shorter reporting periods result from the generally shorter project makespan in deconstruction.

2.4 Summary and conclusions

Section 2.1 describes important terms used in the deconstruction industry for a profound understanding of the processes. Section 2.2 outlines the numerous current legal conditions on EU, national and regional level, and freedoms of actions of deconstruction companies. Especially, changed legal conditions such as the planned ErsatzbaustoffV are important that will affect deconstruction industries' practice in planning and executing deconstruction projects, recycling options and waste handling in the near future.
Section 2.3 describes the main deconstruction stages with the related decisions that have to be made during project duration, e.g. regarding the degree of deconstruction, the required activities, techniques and necessary resources, the technique suitability or the activities' precedence. In the course of project planning in retrofit and deconstruction projects often a building auditing is performed. Thus, recent building auditing and building modeling approaches are classified and shortly described along with their advantages and disadvantages with respect to

applicability in existing buildings and deconstruction sites. Also, this section includes an overview on deconstruction planning in practice, deconstruction preparation such as site clearance and decontamination, deconstruction techniques and their applicability as well as reuse, recycling and disposal practices.

Due to increased recycling requirements, deconstruction of buildings and infrastructures changed considerably during the last decades from a disposal industry to a collecting and processing industry of secondary raw material. Along with recent studies and findings regarding hazardous materials and their health and environmental impacts, a vast amount of laws, guidelines and standards evolved during the last years. These regulations affect the generation, the separation and transportation of waste, the RC material quality and testing, the further use of RC material, the jobsite safety, and the environmental impacts especially regarding neighboring people and soil. Thus, deconstruction of buildings and infrastructure requires as much knowledge and project management as new construction projects where numerous legal regulations regarding both the building deconstruction and material handling (incl. recycling and disposal) have to be met.

Main characteristics of deconstruction projects are time and cost pressure and relative short project durations (days, weeks or few months) depending on the object size. To depict buildings with deconstruction scope, models are adequate that are based on building physics and depict technical conditions and status of a building or project. Today manual building auditing is based on subjective notes taken during onsite inspections, depending on the inspectors' knowledge, experience and available time. Exact mass calculation often requires a very high effort (Lippok and Korth 2007 p. 117ff.). Thus, often simplifications and assumptions are used as a basis for project planning and decision making. And, technical equipment's' masses are often disregarded in mass estimations due to their diversity in configurations, unless building element masses are available in building documentation (Lippok and Korth 2007 p. 117ff.). If only external dimensions or gross volume (GV) of a building are depicted in bidding documents, it might result in inadequate judgments and a higher planning risk based on deviations from estimated mass and material values that often lead to supplement offers, litigation or insolvency (Lippok and Korth 2007 p. 117ff.). This suboptimal information management in deconstruction objects and projects that has to be considered in project planning methods.

As well, other framework conditions can impede deconstruction projects, such as a low importance, low perceived value added and the often neglected need for pre-investigation (building auditing) and detailed planning (e.g. especially lacking deconstruction statics) (Lippok and Korth 2007 p. 50f.). Moreover, restricted space availability onsite, the necessity of improvisation as a result of work-related and onsite changes as well as the mutual exposure of staff and machines due to simultaneously performed deconstruction activities at the same location (Lippok and Korth 2007 p. 50f.) show the need for flexible, operative project and risk management. Other challenges are the need to maintain public transport or near (production) processes, the immediate vicinity of deconstruction activities to intact supply lines or the inadequate handling of technical equipment resulting in high fire or explosion danger caused by deficient cleaning of explosive dusts or media (Lippok and Korth 2007 p. 50f.). All these issues indicate the need for a robust or resilient project management, handling uncertainty and changes or disturbances during project execution.

3 Project management and decision making under uncertainty

The following chapter 3 describes the state-of-the-art project and risk management in general and in the application area of building deconstruction. Section 3.1 introduces important definitions in project management, provides and overview on project indicators and currently available project management software. Section 3.2 describes the main concepts in risk management, as well as robustness and flexibility concepts and shows main risk preferences in decision making. Section 3.3 provides an overview on project planning and scheduling methods under uncertainty in general. Section 3.4 characterizes deconstruction projects and section 3.5 describes and reviews research approaches in building and infrastructure deconstruction planning. This is followed by a conclusion with main findings and the identification of research gaps.

3.1 Terminology in project management

This section provides a definition of projects, project structures, project management in general as well as on project indicators and currently used project software.

3.1.1 Projects and project structure

Projects can be defined as undertakings with unique framework conditions, such as scope, timely, financial, personal or other restrictions, separation from other undertakings or a project-specific organization (DIN 69901-5:2009-01, 3.44; ISO 21500:2013-06, 3.2). Often, several framework conditions are preset, such as deadlines, budgets, availability of resources, factors of health, safety or skills, level of acceptable risk, potential social or environmental impacts or regulations (E DIN ISO

21500:2013-06, 3.11). Furthermore, projects can be distinguished according to project scope, products, projects size, project complexity, project makespan and number stakeholders (DIN 69901-1:2009-01, 4.1). Internal and external projects (with warranty obligation) can be divided according to their commissioner and also unique or routine projects can be differentiated (with similar framework conditions) (Zimmermann et al. 2006 p. 2f.). Internal projects are often commissioned by the upper management of a company, while in external projects, the project result is a product or service for an external client that is often specified in a functional specification document (Zimmermann et al. 2006 p. 2f.). In this research contribution, external routine projects with unique framework conditions are in the focus.
Projects under uncertainty are subject to different kinds of project disruptions that can be caused by (Demeulemeester and Herroelen 2009 p. 5; Elkhyari et al. 2003 p. 1, 2004; Van de Vonder et al. 2008 p. 723):

- time-related uncertainties affecting precedence or imprecise estimations of activity durations than primarily expected;
- activity-related uncertainties resulting in additional, omitting or adapted activities that might have to be inserted in the schedule or have changed resource demands;
- resource-related uncertainties, resulting in changing resource capacities or availability.

These mentioned uncertainties often lead to undesirable schedule disruptions, schedule infeasibility and project delay or cost overrun. “It is well known that replacing random durations with their expected values always result s in an underestimate of the expected duration of the project” (Elmaghraby 2005 p. 310). To handle these uncertainties, several approaches were developed in recent years that are shortly presented in the following subsections.

Depending on each project, a project structure needs to be defined and subsequently individual project management forms and methods can be

applied (DIN 69901-1:2009-01, 4.1). Projects are structured in a work breakdown structure (WBS) as a list or diagram (DIN 69901-5:2009-01, 3.82) with subprojects, work packages and activities as well as the relationships among themselves (DIN 69901-5:2009-01, 3.79). A WBS can be structured object oriented, function oriented or phase oriented (DIN 69901-3:2009-01, 4.4.2). In practice, a WBS often has a mixed structure of the previously mentioned types.
In jobsite projects, also location breakdown structures (LBS) are used to schedule project activities and manage resources (Kenley and Seppänen 2010). Main challenge is the determination of the distinct locations (e.g. according to their hierarchical order: building → building parts → floors → rooms). Main field of application of LBS is the construction industry, whereas in deconstruction projects this method is not applied yet.

3.1.2 Project management and project resources

Project management (PM)[1] is the use of persons and their knowledge and skills as well as tools and methods on project activities to meet project requirements or to achieve project objectives under resource constraints (Ebert 2006 p. 151; Zimmermann et al. 2006 p. 2). Project management includes selection and initiation, planning, direction, operation, and control of a project (Artigues et al. 2013 p. 176; Ebert 2006 p. 151) (DIN 69901-5:2009-01, 3.64, ISO 21500:2013-06, 3.3). According to project management theory, there are several knowledge areas (PMBoK) or project management processes (DIN 69901-2:2009-01, ISO 21500:2013-06, 4.2) that have to be considered during management of a project such as stakeholder, scope, communication, time, cost, quality or risk management (Project Management Institute (PMI) 2013). As projects have an unique character with interdisciplinary cooperation and often cannot be standardized, their technical, financial and scheduling risks are increased (Zimmermann et al. 2006 p. 2). However, in the

[1] For an comprehensive overview on project management see e.g. DIN 69901-5:2009-01, or ISO 21500:2013-06 or (Corsten et al. 2008; Project Management Institute (PMI) 2013).

here focused routine projects with foreseeable uncertainty[2], risks can be estimated via expert knowledge and their expected or experience values (Zimmermann et al. 2006 p. 2).

Projects and their management proceed through five major project phases: initiation, definition, planning, monitoring/controlling and closing (DIN 69901-2:2009-01, 4.1.4) (Ebert 2006 p. 151; Zimmermann et al. 2006 p. 4). The initiation includes the project start and selection of the project time frame, while the definition phase defines and regulates the project scope by contract. The planning phase includes the planning of the activities and resources necessary to fulfil project scope, while in the controlling phase target-performance comparisons and a variance analyses are performed. Finally, the closing ends the project with a closing meeting and the disorganization of project team and structure. In this research contribution, the focus lies on the second and third project phase of definition of project activities and planning of activities and necessary resources.

Project resources are defined as units of workforce, financial resources, physical resources, information, natural materials and supporting means that are necessary to perform project activities (DIN 69901-5:2009-01, 3.91). Resources can have different types: renewable, non-renewable, doubly constrained, cumulative etc. and are typically limited or constrained. The resource demand of an activity is defined as the number or quantity of a single resource or multiple resources (also of different types) that are necessary to perform the activity (DIN 69901-5:2009-01, 3.92). Often, the estimation of resource demands of project activities is an iterative process (DIN 69901-3:2009-01, 4.1.1) due to their uniqueness and part of the project management. In this research contribution, resource demands focus on renewable resources (time) and non-renewable resources (cost) due to their relevance in deconstruction projects. Project time, resource and cost estimates are often subject to incomplete information and uncertainty (DIN 69901-3:2009-01, 4.1.1.).

2 See section 3.2.1 for a definition of unforeseeable and other types of uncertainty.

There are a number of alternative ways to estimate project parameters (e.g. activity durations) in project management, including past experience, expert opinion, and mathematical derivation (Pinto 2012). Regarding time estimate methods, there are several methods such as expert estimate, Delphi method, three-point method or project comparison (DIN 69901-3:2009-01, 4.1.2.). The estimate is calculated by the mean of the three values; often the realistic value is weighted four times (DIN 69901-3:2009-01, 4.1.2.). The typical expression is an optimistic, most likely, and pessimistic estimate, which gives rise to the fuzzy set theory to describe the uncertainty e.g. of activity durations (Pinto 2012) (DIN 66901-3:2009-01). In this work, the three-point method for estimation of activity durations is applied, including an optimistic, realistic and pessimistic value (see also section 4.3).
Often, miscalculation or adaptation needs occur in real projects and lead to recursions to earlier project processes (planning stage) that are associated with e.g. rescheduling or reorganization (DIN 69901-2:2009-01, 4.1.4). Thus, prevalent temporal sequences in real projects might be non-linear and dynamic (DIN 69901-2:2009-01, 4.1.4) and are contradictory to the mainly applied linear and non-dynamic project planning methods.

3.1.3 Project indicators

Project indicators are applied in several fields such as project delivery, financial performance, health/safety and security performance, environmental performance and socio-economic performance (IAEA Nuclear Energy Series 2011 p. 17) (see Figure 3-1). The establishment and monitoring of indicators related to project stages enables decision makers to better plan, monitor and control projects. Main indicators for project teams and project managers focus on project delivery, financial performance and health/safety and security (IAEA Nuclear Energy Series 2011 p. 15). The report of IAEA describes many potential sub-indicators in these areas. Depending on the type of project and the application area, different project indicators are preferred by and useful for decision makers and project managers.

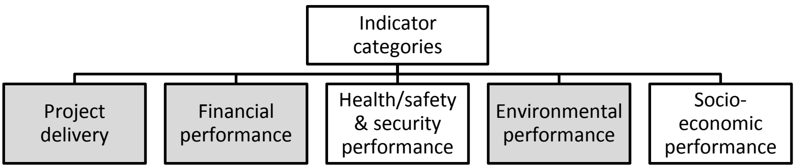

Figure 3-1: Indicator categories in projects[3]

Also with respect to building deconstruction projects, indicators in project delivery, financial performance and safety seem amongst others the most relevant indicators for decision making and project planning and controlling. Main used indicators in deconstruction industry today for project delivery are gross volume (GV) or total enclosed space and gross floor area (GFA) of the building. In financial performance, main indicators in deconstruction projects include total project cost, total project makespan or number of employees at the project. Table 3-1 shows further indicators that might be used, to improve project and risk management in deconstruction projects.

During project execution, total project cost and total project makespan can be tracked in an earned value analysis comparing planned value, actual value and earned value and further analyzed in a trend analysis. However, as the research contribution focuses on project planning rather than on project controlling, several project planning indicators of Table 3-1 such as total project makespan, total cost or gross volume and mass are calculated prior to project start to enable later project controlling.

[3] According to (IAEA Nuclear Energy Series 2011 p. 17).

3.1.4 Project management software

During the last decades, project planning and management methods were transferred into practice by respective software implementation in standard and specialized software (Bartels 2009 p. 37; Kolisch 2001). Current landscape of project management (PM) software is divers (Corsten et al. 2008 p. 245ff.). Software packages differ in project size, risk class, complexity of precedences, dependencies and interrelations, resource diversity or user friendliness (Corsten et al. 2008 p. 245ff.). Today, approaches of network planning to calculate the shortest project makespan and to determine the critical path are broadly implemented in commercial project management software (Bartels 2009 p. 1). However, the general project scheduling software like Microsoft Office Project (Microsoft Corporation), Primavera Project Planner (Oracle Corporation) or PS8 (Sciforma Corporation) are widely used but are more or less based on scheduling approaches from the 60ties and 70ties (Demeulemeester and Herroelen 2009 p. 17; Kolisch 2001).

Mainly used software is Microsoft Project that depicts activities with their resource demands and precedence their relationships. Activities can be grouped into project phases and can have predefined time frames for their realization. Milestones can be inserted to depict the attainment of a desired project status. Resources are differentiated in potential and repetitive factors and capacity utilization can be depicted. Thus, Microsoft Project is a useful tool for project management in general because it provides basic project management utilities, such as calendar, resources' assignments and workloads and monitoring project activities (Salas-Morera et al. 2013 p. 182). But, it does not allow stochastic analyses as it considers average values for activities' durations (Salas-Morera et al. 2013 p. 182).

Primavera P6 Project Planner (Oracle) is professional software especially designed for multi-project purposes. For the solution of single projects, only CPM is applied which does not allow considerations about uncertainties (Salas-Morera et al. 2013 p. 183). But often, only simple heuristics are implemented in commercial software for capacity optimization (Domschke and Drexl 2007 p. 120).

Table 3-1: Relevant exemplary project indicators of project delivery, financial and environmental performance categories for deconstruction projects[4]

Project delivery	Financial performance	Environmental performance
• total project makespan [h] • schedule of activities and planned resource allocation • resource and location capacity usage/utilization in the course of the project (resource levelling) • number of elements on the critical path* • progress performance with delays (earliness/ tardiness)* [h], on-time activities [#] and interruptions [#] • gross volume and mass	• total project cost [€] • cost curve in the course of the project [€/h] • decontamination cost [€], [%] • deconstruction cost [€], [%] • recycling and disposal cost [€], [%] • recovery costs per material [€/kg or €/t] • cost deviations*	• used renewable primary energy° (PERT) [MJ] • used non-renewable primary energy° (PENRT) [MJ] • use of secondary raw materials° (SM) [kg] • use of freshwater° (FW) [m³] • disposal of hazardous materials°° (HWD) [kg] • disposal of non-hazardous materials° (NHWD) [kg] • Components for reuse (CRU) [kg] • recycled material (MFR) [kg] • energy-retrieving materials (MER) [kg] • recycling rate [%], (HQ/LQ) • disposal rate [%] • environmental impact indicators per material/ building element [LCA categories] or savings compared to other recycling path
*: indicator for risk assessment and ranking of deconstruction schedules, °: input indicator °°: output indicator		

4 Partly based on LCA indicators in ökobau.dat.

A comparison of minimal project makespan of resource-constrained project scheduling problems solved by commercial project management software and by state-of-the-art solution procedures showed considerable differences (Mellentien and Trautmann 2001 p. 383; Trautmann and Baumann 2009a p. 1143). It turned out that PM software calculates considerably higher project makespan and that the gap increases significantly with the number of project activities and the resource scarcity (Trautmann and Baumann 2009a p. 1148). Also, solutions found by Primavera were superior to those of Microsoft Project (Trautmann and Baumann 2009a). Even applied in a real construction project, the available software packages perform quite differently, show noticeably longer project makespan than in the best known feasible schedules and resulting project makespan strongly depends on the used priority rules (Trautmann and Baumann 2009b p. 632).
Problem specific software uses more modern project management approaches (Kolisch 2001). But, the diffusion of exact scheduling procedures into practices remains extremely low partly owed to the fact that real-life RCPSP with >100 activities are still beyond solvability (Demeulemeester and Herroelen 2009 p. 31) despite continuous improvements of solvers and computer performances with respect to storage capacity and computing power. “Surveys also indicate that many companies mainly use project planning software for communication and representation” (Demeulemeester and Herroelen 2009 p. 17) and not for project management.

There is also educational scheduling software e.g. RESCON, ProMES, PpcProject, LEKIN, LiSA and TORSCHE that is described and discussed with respect to the model requirements and the application case in the following:
LEKIN® version 2.4 scheduling software is accompanying the work of Pinedo and his colleagues and can be downloaded for free (Pinedo et al. 2002). Its latest version from April 2002 is able to deal with flexible job shop problems that process jobs on several machines with a defined

number of operations per job. The operations or jobs can be assigned to specific machines. However, LEKIN does not depict multi-mode job shop scheduling problems with differing activity durations per mode. Also, the input of jobs, machines and operations is manually and time-consuming. A potential interface or data import/export function is not provided. Applicable solution methods follow several rules (EDD, WSPT, SPT, LPT) or heuristics (shifting bottleneck, local search, decomposition approaches)[5].
A similar system LiSA version 3.0 (A Library of Scheduling Algorithms, GNU GPL) has been developed for general scheduling purposes of different problem classes at the Otto-von-Guericke-University Magdeburg by Andresen and his colleagues (Andresen et al. 2010). This system is similar to LEKIN, but is able to identify the complexity of a scheduling problem via a literature database. Solution methods include branch-and-bound, beam search, sequencing and iterative rules, simulated annealing and taboo search. However, it is also not able to depict and solve multi-mode scheduling problems with precedence relations and deadline.
TORSCHE scheduling toolbox version 0.5.0 for MATLAB is also a freely (GNU GPL) available toolbox of scheduling algorithms created by a research team around researchers Kutil, Hanzálek, Šůcha and Sojka of the Centre for Applied Cybernetics, Department of Control Engineering of Czech Technical University in Prague (Kutil et al. 2007; Dvorak 2015). This toolbox includes a plethora of deterministic scheduling algorithms and heuristics such as list scheduling or Horn’s algorithm. However, this toolbox is limited to smaller, deterministic machine scheduling problems yet and the formulated a job shop scheduling problem (MRCPSP) was not solvable by the available methods of the toolbox.
The description of RESCON, ProMES and PpcProject and also the original literature can be found in (Salas-Morera et al. 2013 p. 182) for an overview of the mentioned tools. Moreover, there is a comparison and discussion of these tools with commercial, free and academic project management tools. However, although PpcProject does use PERT method,

[5] See also section 4.4.4.

none of the presented tools do consider scenario construction in the calculation of activity durations.

3.2 Terminology of uncertainty and risk

3.2.1 Risk, uncertainty and severe uncertainty

"Uncertainty is defined as the difference between the amount information required to perform a particular task and amount of information already possessed by the organization" (Galbraith 1973 p. 5). Uncertainty can also defined as the future state or development without an assignable probability (Scholl 2001 p. 56). However, the following sections are based on the first definition.

Decision theory distinguishes certainty, risk and severe uncertainty or ignorance (Artigues et al. 2013 p. 177; Müller 1993). In the case of risk, the possible impacts and the probability of occurrence of an event are known, but not the time instant when the event occurs (Artigues et al. 2013 p. 177; Müller 1993). In the case of severe uncertainty (ignorance), possible impacts and its examined alternatives is not completely known but without information of their probability of occurrence or time instant (Müller et al. 1993). And, "the greater the uncertainty the greater the amount of information that must be processed among decision makers during task execution in order to achieve a given level of performance" (Galbraith 1973 p. 5).

In uncertainty analysis and risk management a plethora of different uncertainty types are defined. With respect to models, uncertainties often are divided into (I) aleatoric uncertainty and (II) epistemic uncertainty (Bertsch 2008; Comes 2011 p. 20; Reuter 2013). Other sources of energy demand modelling, of LCA assessment or building retrofitting further classify (III) heterogeneity und (IV) ignorance (Booth et al. 2012; Chouquet 2007; Firth et al. 2010; Kiureghian and Ditlevsen 2009; Reuter 2013; Yuventi and Weiss 2013):

Aleatoric uncertainty (random or chance variability) are characterized by variability and usually are described in models by probability distributed random variables (Comes 2011 p. 20; Reuter 2013). To estimate respective probability distributions inductive statistics with parametric or non-parametric methods have to be applied (Reuter 2013). Variability depicts the alterability or change in elements of a sample, e.g. measurements of a quantity to be measured at different measuring points (Reuter 2013) and thus is the natural lower bound of uncertainty quantification (Min and Hense 2005). Aleatoric uncertainties are not reducible by nature (Comes 2011; Kiureghian and Ditlevsen 2009). “While aleatoric uncertainty (random or chance variability) is a property of the observed system, epistemic uncertainty belongs to its observer” (Bertsch 2008).
Epistemic uncertainty result from a certain level of ignorance (deficient knowledge) of the considered system (Comes 2011 p. 20; Min and Hense 2005). Epistemic uncertainties in parameters can theoretically be measured or be quantified/approximated by assumptions or quantitative judgments of experts and mathematically formulated by fuzzy logic (see section 3.3.2) in decision theory (Comes 2011 p. 20; Reuter 2013). In contrary to aleatoric uncertainty, epistemic uncertainty can be reduced by research, measurements/gathering information or statistical analysis associated with additional expenses (Bertsch 2008 p. 45; Comes 2011; Merz 2011 p. 145; Min and Hense 2005). Booth et al. differentiates here the often prevailing “assumptions“, (e.g. rational simplifications or assumptions on element lifetimes) with incomplete information and the theoretically measureable “state-of-the-world“, (e.g. measureable in comprehensive site inspections or expert measurements) that might contribute to uncertainty reduction (Booth et al. 2012; Kiureghian and Ditlevsen 2009). As process steps might include both aleatoric and epistemic uncertainty, a final assignment to the described uncertainty types may not always be possible but depends on modeling (Volk et al. 2013). Heterogeneity results from variation of elements or element properties in clusters (Volk et al. 2013). This might be the case, if building materials or scenarios are grouped to clusters despite their slightly

different properties. This will be further discussed in section 4.3. Ignorance describes the lacking knowledge and uncertainty about the qualitative design/form/structure of the system or process under consideration that has to be modeled (Booth et al. 2012; Volk et al. 2013). This potentially inadequate modeling is hardly quantifiable and is inherent to all models (Bertsch 2008). If aleatoric uncertainties are not considered/anticipated in a model structure, also ignorance is prevailing (Kiureghian and Ditlevsen 2009). Thus, differentiation of aleatoric uncertainty and ignorance often is not possible (Volk et al. 2013). However, ignorance is not further considered in this paper.

In project management and decision making, also four major types of uncertainties in project management might occur: variation, foreseen uncertainty, unforeseen uncertainty and chaos (De Meyer et al. 2002).

Variation might include small changes in project activities such as delays of starting times or unanticipated difficulties leading to minor schedule changes (Demeulemeester and Herroelen 2009 p. 37). Variation or aleatoric uncertainty (random or chance variability) in general depict the alterability or change in elements of a sample, e.g. measurements of a quantity to be measured at different measuring points (Reuter 2013) and thus is the natural lower bound of uncertainty quantification (Min and Hense 2005). Variation is usually described by probability distributed random variables (Comes 2011 p. 20; Reuter 2013). To estimate respective probability distributions, inductive statistics with parametric or non-parametric methods have to be applied (Reuter 2013). Variability is a property of the observed system (Bertsch 2008) and is not reducible by nature (Comes 2011; Kiureghian and Ditlevsen 2009).

Foreseen uncertainty includes well-understood uncertainty but their probability of occurrence and their occurrence in the present project is not clear (e.g. depicted in scenarios). Based on foreseen uncertainties, contingency plans can be developed (Demeulemeester and Herroelen 2009 p. 37). Foreseen or epistemic uncertainty result from a certain level of ignorance (deficient knowledge) of the considered system (Comes 2011 p. 20; Min and Hense 2005). Epistemic[6] uncertainties in parameters can theoretically be measured or be approximated by assumptions or quantitative judgments of experts and mathematically formulated by fuzzy logic (see section 3.2.5) in decision theory (Comes 2011 p. 20; Reuter 2013). In contrary to aleatoric uncertainty, epistemic uncertainty “belongs to its observer” (Bertsch 2008) and can be reduced by research, measurements, information gathering or statistical analysis associated with additional expenses (Bertsch 2008 p. 45; Comes 2011; Merz 2011 p. 145; Min and Hense 2005). Booth et al. differentiates here the often prevailing „assumptions“, (e.g. rational simplifications or assumptions on element lifetimes) with incomplete information and the theoretically measureable „state-of-the-world“, (e.g. measureable in comprehensive site inspections or expert measurements) that might contribute to uncertainty reduction (Booth et al. 2012; Kiureghian and Ditlevsen 2009). As process steps or project parameters might include both aleatoric and epistemic uncertainty, a final assignment to the described uncertainty types may not always be possible (Volk et al. 2013).

Unforeseen uncertainty cannot be identified during project planning (Demeulemeester and Herroelen 2009 p. 37) and often evolve in technology development projects, research projects or disaster management projects during project execution.

Chaos has a unknown project structure, unknown assumptions and objectives (Demeulemeester and Herroelen 2009 p. 37). If aleatoric uncertainties are not considered in a model structure, also ignorance is prevailing (Kiureghian and Ditlevsen 2009).

[6] Further concepts are heterogeneity and ignorance. Heterogeneity results from variation of elements or element properties in clusters (Volk et al. 2013). This might be the case, e.g. if building materials or scenarios are grouped to clusters despite their slightly different properties. This is further discussed in section 4.3. Ignorance describes the lacking knowledge and uncertainty about the qualitative design and structure of the system or process under consideration that has to be modeled (Booth et al. 2012; Volk et al. 2013). This potentially inadequate modeling is hardly quantifiable and is inherent to all models (Bertsch 2008) .

Thus, differentiation of aleatoric uncertainty and ignorance often is not possible (Volk et al. 2013).

As deconstruction projects are routine projects in changing framework conditions, in the following research contribution, variation and foreseeable uncertainty (known unknowns) is considered. Thus, deconstruction projects focus on decision making and project planning under foreseeable uncertainty, where the optimal or robust solution might not be obvious but need decision support. Unforeseen uncertainty can also occur, e.g. when building statics yield unexpectedly or neighboring buildings are damaged by unexpected earth movements. However, these aspects as well as chaos are not in the focus of the research contribution and are not further considered, but at least unforeseeable events might be included in future research.

Aytug et al. further differentiate cause, context, impact and inclusion[7] of data and parameter uncertainty in scheduling models as the four issues that influence scheduling problems (Aytug et al. 2005 p. 92). Causes or sources of uncertainties are numerous and can result in deconstruction scheduling problems from materials, processes, resources, tooling or personnel (see section 4.3.1). In project execution, often activity durations do not correspond to their initially estimated values due to uncertainties. Thus, project makespan, schedule and project cost can tremendously change (Aissi and Roy 2010 p. 94; Hazir et al. 2010 p. 633). Uncertainties' impacts are either context-free or context-sensitive where the latter requires additional information on the respective situation. Impact describes the result of uncertainty (Aytug et al. 2005 p. 92), that might influence schedule and precedences, resources or quality e.g. prolongation or shortening of activity duration, additional or omitting activities, resource availability, effects on or changes in starting times and due dates, effect on single or multiple activities. Uncertainty can be

[7] See sections 3.2.5 and 3.3 for the inclusion of uncertainties into project scheduling.

included predictively or reactively into project scheduling. In literature, activity and resource uncertainty is often addressed (Demeulemeester and Herroelen 2009 p. 89) and uncertainty is mainly considered context-free (Aytug et al. 2005 p. 92).

Decision making under certain and uncertain conditions can be differentiated into four areas; simple, complicated, complex and chaotic situations with different characteristics (Snowden and Boone 2007) (see Figure 3-2), that are described in the following according to Snowden and Boone. Decisions under certainty or simple situations include deterministic situations with complete information and knowledge about the system and thus are the basis for deterministic decision models (Scholl 2001). Deterministic planning is not capable to cope with unknown future developments, information gaps or information update (Gebhard 2009 p. 34). In decisions under risk and severe uncertainty at least intervals of uncertain parameters are known and are processed in fuzzy or stochastic planning (see section 3.2.5). Furthermore, either (objective or subjective) probabilities or possibility of occurrences for (all) possible scenarios[8] or parameter constellations (a) are known and form a stochastic or fuzzy decision model (decision under risk) or (b) are not known and decisions are made under (severe) uncertainty (Scholl 2001). Here, complicated situations are theoretically knowable (with foreseeable uncertainty, 'known unknowns'), but often to extensive possibilities or alternatives occlude the existing, optimum decision. Complex situations include unforeseeable uncertainty ('unknown unknowns'), making an "optimal" decision and any anticipation hardly possible. Chaotic situations include constantly shifting situations without traceable cause-effect-relationships ('unknowables'). As in routine building deconstruction projects all possible alternatives are theoretically known, this research focuses on complicated situations that are in need for systematic analysis for the best decision.

[8] For the definition of 'scenario' see section 3.2.5.

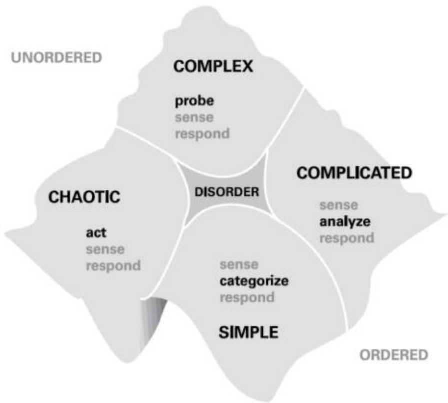

Figure 3-2: Types of decision making situations[9]

Other major concepts of decision making under uncertainty include the time aspect via "expected-value", "wait-and-see" and "here-and-now" approaches (Birge and Louveaux 2011; Elmaghraby 2005; Heitmann 2010; Koberstein 2013; Madanski 1960). Expected-value approaches calculate the optimal schedule via expected input parameters and apply the optimal decision in all scenarios. This leads to major disadvantages. Wait-and-see approaches reactively calculate the distribution of objective values for all scenarios and recalculate after an unexpected event. But, they do not provide a decision recommendation prior to project start. Here-and-now approaches calculate a feasible, optimal solution for all scenarios based on the available information, due to the necessity to plan prior to project start. A comparison of the different approaches can be performed with the indices of expected value of perfect information (EVPI) and the value of the stochastic solution (VSS)[10] depicting the additional value generated through considering uncertainty in the decision making process.

[9] According to (Snowden and Boone 2007).
[10] For the definition of EVPI and VSS see section 3.3.1.

3.2.2 Project risk and risk management

Risk[11] can be defined as a probability distribution of loss (Munier 2014 p. 1; Paulos 2001) or as the impact of uncertainty onto objectives, characterizing both threads and chances (Ebert 2006 p. 7). Mostly, risks are further specified to negative deviations from project planning due to foreseen or unforeseen events or the absence of a planned event (DIN 69901-5:2009-01, 3.77). Risks are associated with a probability of occurrence and thus, the expected risk can be quantified by the product of expected extent of damage and the risks' probability of occurrence. The estimation of a risks' probability of occurrence and of its impact on project scope, time and cost can often be generated from assessment of statistical data, cost/scheduling calculation and expert judgment via point or interval estimation (Girmscheid and Busch 2014 p. 94).

Risks result from external or from internal factors (ISO 21500:2013-06, 3.5) that influence projects and that can include e.g. (Munier 2014 p. 6ff):

- Performance, scope, organization structure/ culture, quality, and technology issues;
- Environmental, safety, and health concerns;
- Cost and schedule uncertainty, resource availability, maturity level of project management;
- Political or legal concerns.

As internal factors can rather be managed by the integration of their uncertainties and risks in operative resource allocation (Elmaghraby 2005 p. 308), this research contribution focuses on foreseeable, internal project uncertainties and risks.

[11] For the definition of risk see section 3.2.1. Further risk definition of cause and effect related risk, risk in the narrow (asymmetric) and broad (symmetric) sense can be found in e.g. (Girmscheid and Busch 2014 p. 39f.; Munier 2014 p. 21). See also (Munier 2014 p. 6ff) for further examples of internal and external risks.

Risk management[12,13] (in projects) is a systematic, continuous process including the application of management principles, methods and practices to identify, assess (analyze and evaluate), handle, control and communicate potential risks (Demeulemeester and Herroelen 2009 p. 39; Ebert 2006 p. 151; Wengert and Schittenhelm 2013 p. 2) (DIN 69901-5:2009-01). Risk analysis includes the identification and evaluation of risks, while risk assessment tries to quantify probability of occurrence and potential damage (DIN 69901-5:2009-01). In literature, risk management is seen as an integral part of project management (DIN 69901-2:2009-01, ISO 21500, 4.2). The aim of risk management is to avoid, response, reduce, transfer (e.g. insurance), mitigate or accept risk impact on project objectives (Borghesi and Gaudenzi 2013; Issa 2013 p. 698; Project Management Institute (PMI) 2013) and to provide respective economically and technically optimal strategies and decision making support.

In corporate risk management, not only existence-threatening risk should be considered but also smaller risks influencing corporate activities and processes (Horváth and Gleich 2000). “Risk management is nowadays a critical factor for successful project management, as projects tend to be more complex and competition increasingly tougher“ (Issa 2013 p. 699). Thus, scenario analyses and sensitivity analyses can be applied to identify and assess specific project risks (Ebert 2006 p. 67; Wengert and Schittenhelm 2013 p. 39).

To identify risks several documents may serve as data input such as management plans for risk, cost, schedule, quality and human resource, as well as estimations for activity cost and duration, stakeholder register,

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[12] See Munier (2014), S. 19 for a comprehensive overview on risk identification, assessment techniques and risk management. More information on risk management can also be found in ISO 31000:2009, *Risk management – Principles and guidelines and* ISO/IEC 31010:2009, *Risk management – Risk assessment techniques*.

[13] Due to the structural similarities of site fabrication in construction and deconstruction projects, objectives like makespan and cost minimization are predominant and the further developed construction risk management is also shortly reviewed and analyzed.

project and procurement documents, or environmental or organizational factors (Project Management Institute (PMI) 2013). Risk identification methods in practice are documentation reviewing, brain storming, Delphi technique, interviewing, root cause analysis, checklists, assumptions, diagramming (cause-effect diagrams, system or process flow charts or influence diagrams), SWOT analysis regarding Strengths, Weaknesses, Opportunities, and Threats or expert judgment (Girmscheid and Busch 2014 p. 59; Project Management Institute (PMI) 2013). The risk register (listed risks) includes information on the risk identification date, the risk likelihood (probability of occurrence), the risk impact, a risk classification (for prioritization) and potential control measures. High-priority risks are further assessed quantitatively via sensitivity analysis, expected monetary value analysis (EMV), activities' time and cost modeling and simulation based on probability distributions (fuzzy, beta, triangular, uniform, normal, lognormal).

In literature, risk categories are defined heterogeneously (Girmscheid and Busch 2014 p. 41). The Guide of Project Management Body of Knowledge (PMBoK) classifies four main project risk categories of technical, external, organization and project management risks with further sub-risks in a risk break down structure (RBS) (Project Management Institute (PMI) 2013). Others divide risks into strategic[14] risks affecting corporate objectives such as existence, competitiveness or profit maximization, as well as hazard risks, financial risks and operational risks (affecting project objectives) risks (Borghesi and Gaudenzi 2013 p. 117; Merz 2011 p. 11; Wengert and Schittenhelm 2013 p. 26). For construction projects, (Girmscheid and Busch 2014 p. 41) recommend a risk classification into: legal risks, time risks, financial risks, technical risks, management risks and external/environmental risks. Figure 3-3 shows the recommended risk categories that might be a valuable risk classifica-

[14] For strategic or corporate risk management see ISO 31000 (2009) or e.g. (Wengert and Schittenhelm 2013).

tion for deconstruction projects, too, due to structural project similarities on construction and deconstruction projects. Schatteman et al. however, follow a different risk categorization that is more adapted to construction industry needs with: environment, organization, consumer goods, workforce, machines and subcontractors (Schatteman et al. 2008 p. 4f.). In deconstruction project however, risk categories might vary e.g. there are less subcontractors involved in deconstruction projects (except for nuclear power plants), consumer goods are restricted to operating supplies such as fuel and instead the market developments of (raw) material prices are decisive.

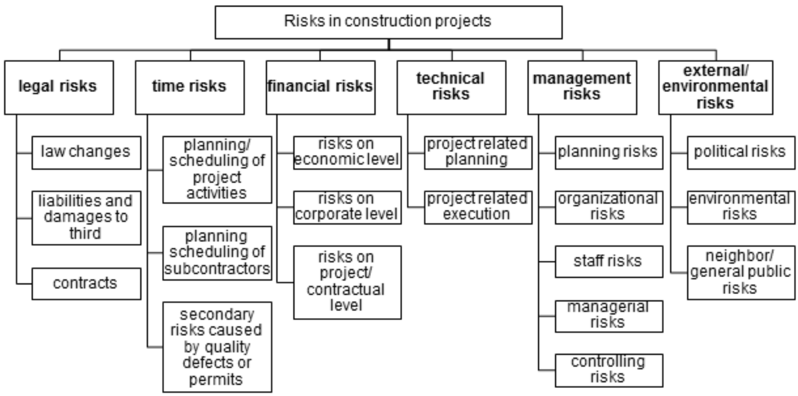

Figure 3-3: Risks in construction projects[15]

Strategic risks include long-term influences on organizations that have to be addressed to not endanger the whole enterprise (Ebert 2006 p. 24). Financial risks consist of interest change risk, market value risk, exchange rate risk, raw material risk, default risk or balance of accounts risks. Operational risks are subdivided into staff risks, technology risks, process risks, market risks and external risks (e.g. ecological risks) (Wengert and

[15] According to (Girmscheid and Busch 2014 pp. 40–52).

Schittenhelm 2013 p. 26). Process risks include uncertainties in time, cost and resource estimations which are of specific interest in this research contribution. Operational risks influence makespan, cost, content, quality or functionality of projects (Ebert 2006 p. 24). Legal risks can be caused by laws, damages to third parties or contracts (Girmscheid and Busch 2014 p. 41). Especially in industrial production processes, technology risks are important that include technical disruption of production processes or generally absence of process safety (Bertsch 2008; Merz 2011 p. 13). Causes of technical risks can be process-inherent or external (Elmaghraby 2005 p. 308; Merz 2011 p. 13). Operational processes represent the core business of most companies, and therefore the proper assessment of operational and supply chain risks is critical […] for the organization" (Borghesi and Gaudenzi 2013 p. 117). Table 3-2 shows examples of potential operative risks that might occur in deconstruction projects.

Table 3-2: Exemplary operational risks in deconstruction projects

Operational risk category	Potential risk occurring in deconstruction projects
Staff risk	• Unqualified staff • Changing labor productivity of staff • Poor coordination among staff or subcontractors/parties • Inadequate and slow decision-making mechanism
Technology risk	• Application of outdated techniques (e.g. of sampling, sorting) causing risks of liability, image damage, penalties and market risks • Inefficient use of equipment • Rework due to error in execution
Process risk	• Contractual penalty at overrun of project makespan or budget • Additional cost due to unexpected building elements or hazardous materials • Legal risks (e.g. liability)
Market risk	• Price changes of produced goods (future cash flows) • Price changes at recycling or disposal facilities • Denied additional claims
External risk	• Environmental policy • Economic development of the industry or country, e.g. demand for RC material • Weather and natural disasters

Risks of the mentioned categories often are interlinked with and effect each other but ultimately result in financial impact on the corporation (Girmscheid and Busch 2014 p. 52). In this research contribution, the focus lies on foreseeable operational risks (internal risks) that can be integrated into resource allocation or a project. Risks assessment can be performed via qualitative or quantitative probability-impact matrices or ABC analyses (Girmscheid and Busch 2014 p. 95; Project Management Institute (PMI) 2013 p. 318). However, these methods do not solve the operative resource allocation problem. Schatteman et al. propose a promising method to integrate expert based risk assessments into construction project scheduling (Schatteman et al. 2008). They quantify risk probability, created a baseline schedule and successively inserted buffers to maximize both solution and quality robustness of the schedule. For this purpose, they query scenario-based probabilities of occurrences and impacts of risk factors (rescheduling costs represented by activity weights) via qualitative statements that are later on transferred into fuzzy distributions. The tests revealed that other commercial planning tools create significantly longer project makespan at higher average stability costs (Schatteman et al. 2008 pp. 18–20). Especially in large construction projects, risk understanding and risk management is key for all decision makers (Hartmann et al. 2012 p. 609). The same applies for (large) deconstruction projects, where also many uncertainties prevail. Traditionally, risks in construction projects are analyzed tabularly, further explained in reports, Gantt diagrams or sketches (Hartmann et al. 2012 p. 609) and are evaluated via expected risk (costs) (Girmscheid and Busch 2014 p. 63) or expected delay (Schatteman et al. 2008 p. 5). Other approaches try to tackle and quantify risk impact by identifying linguistic makespan-affecting, operative and process risk factors on construction projects' due dates and expected makespan overrun (Issa 2012, 2013; Schatteman et al. 2008). Often, (especially in larger projects) these construction risk values are hardly transferable to other construction projects or even deconstruction projects since the projects are unique. Tools to support risk management and decision processes should be easy

applicable, traceable and (de-)construction stage oriented (Girmscheid and Busch 2014 p. 56). “However, due to the complexity of large construction projects […] [with] different stages of construction, these tools do not allow project managers to, quickly and completely visualize and understand risks, their location onsite, and the risks’ implications on quality, costs and schedule of the project” (Hartmann et al. 2012 p. 609).
Experiences in deconstruction projects show that risk is expected to be decreasing with project progress due to increased information and decreasing residual project complexity towards the end of the project. However, risk management methods are not applied deconstruction projects yet, except for thumbs-rule on security margins to roughly estimate daily operational risks. And, since in deconstruction projects probabilities of occurrence are not always known, the expected risk often cannot be qualified. Thus, in deconstruction risk management practice, rather legal regulations and general liability in the case of harm (personnel, third party) or damage (buildings, infrastructure, environment) is addressed via financial surcharges or assurances (Lippok and Korth 2007), rather than management and their related chances and threads. This research contribution will concentrate on the consideration and integration of operational risks of deconstruction projects affecting project makespan and costs via scenario-based project planning.

3.2.3 Preferences of decision makers

Preferences of decision makers are based on the utility theory of Von Neumann and Morgenstern that increasingly are included and modeled in economics (von Neumann and Morgenstern 1944). Three main types of decision makers can be differentiated with respect to their risk taking (Kall and Wallace 2003 p. 128; Scholl 2001 p. 51): risk-averse, risk neutral and risk seeking that can be described by concave, linear or convex utility functions of the mean μ and standard deviation σ of the respective value (see Figure 3-4). The grey arrow in Figure 3-4 describes the direction of the preferred values, either mean μ, standard deviation σ or a combination of both. Risk aversion can be modeled in a linear and non-linear way and often is included according to Markowitz' mean-variance approach considering the difference from expected value (Markowitz 1959).

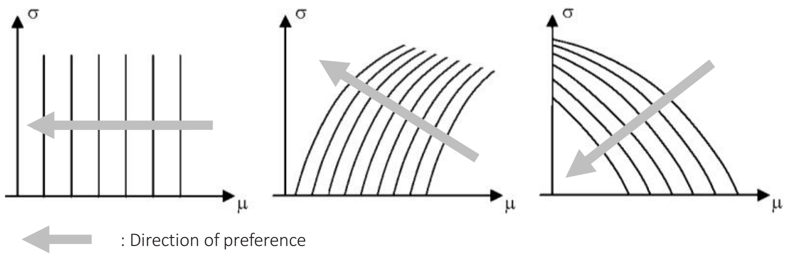

Figure 3-4: Risk preference curves with regard to minimization problems for risk neutrality (left), risk seeking (center) and risk aversion (right) and μ: expectation and σ: standard deviation[16]

Risk preferences depend on personal preferences but also on operational contexts such as the relative importance of a project related to the project portfolio of the decision maker. Subjective preferences of decision makers "constitute a major source of uncertainty" in the decision process (Bertsch 2008).

Due to the unknown future development, in many operational corporate contexts decision makers with risk averse attitude are to be assumed (Gebhard 2009 p. 34; Kall and Wallace 2003 p. 128; Scholl 2001 p. 93). Risk averse decision makers are interested in robust project planning that also include very unlikely scenarios with grave or disadvantageous impacts (Scholl 2001 p. 98,107). As robustness can inter alia induce increased planning stability or flexibility, the following section describes robustness criteria in detail.

[16] According to (Gillenkirch 2016) (accessed: 23.05.2016).

3.2.4 Flexibility and Robustness[17]

Scheduling approaches often assume perfect and complete information at the project planning stage. “During execution, however, a project may be subject to considerable uncertainty […] [where] activities can take shorter or longer than primarily expected, resource demands or availability may vary [or] new activities might have to be inserted.” (Van de Vonder et al. 2008 p. 723) or new information might require schedule adaptions. Flexibility is the ability of a system to adapt to changes as best as possible. Robustness describes the ability of a system to perform well under different conditions or scenarios (Scholl 2001 p. 93). It can also be defined as the (desired) insensibility of a system under different uncertain, non-anticipated conditions, future developments or scenarios (Gebhard 2009 p. 33; Goerigk and Schöbel 2013; Hazir et al. 2010 p. 634; Scholl 2001 p. 93; Wallenius et al. 2008). In scheduling or resource planning, those decisions, schedules or project plans are robust that react less sensitive to or sufficiently well to perturbations (Hazir et al. 2011; Herroelen and Leus 2005) and perform as best as possible in every imaginable scenario[18] (Scholl 2001 p. 93; Wallenius et al. 2008) or in worst-case scenarios (Hazir et al. 2010 p. 634)[19].

In robustness evaluation of alternative solutions or strategies, several performance values and criteria can be compared to find a robust strategy. “A [strategy] is qualified as robust if its performance varies little under the influence of […] variation-provoking factors” (Aissi and Roy 2010 p. 96). Robustness criteria can be divided into several concepts that often are not clearly classified (Goerigk and Schöbel 2013 p. 30; Scholl 2001). The following sections follow the definitions of robustness of Scholl (Scholl 2001 pp. 94–108) with respect to project planning:

[17] For more information on flexibility and the difference to elasticity as well as on robustness see (Billaut et al. 2008; Scholl 2001 p. 94, 98ff).

[18] For the definition of ‘scenario’ see section 3.2.5.

[19] For an overview on schedule robustness see (Van de Vonder et al. 2006b) and on robust scheduling see (Herroelen and Leus 2004, 2005)

Quality robustness describes a project plan or schedule that induces maximal objective values (e.g. minimal project makespan) under every possible future development or scenario (Scholl 2001 p. 99). It can also be described as the insensitivity of a schedules' objective function value (e.g. makespan, cost) to disruptions (Hazir et al. 2010 p. 634; Herroelen and Leus 2005; Schatteman et al. 2008 p. 13; Scholl 2001 p. 102). Quantitatively spoken, it discusses the change of the distribution of the objective function/value caused by perturbations. Thus, a schedule with the lowest possible deviations from the scenario-optimal objective value is preferred for each scenario (Scholl 2001 p. 102). Sub categories of this criterion are strict robustness and its gradations of conservatism (Goerigk and Schöbel 2013; Soyster 1973). In the last decade, quality robustness has become a central point of attention in RCPSP research (Herroelen and Leus 2005; Van de Vonder et al. 2006a p. 215). Quality robustness of schedules or plans can be evaluated via a lot of different measures such as mean, (empirical) variance or standard deviation, range or interquartile range or by total or relative regret values or decision rules for each scenario e.g. with Laplace rule (risk neutral), maximin-rule (risk averse), maxi-max-rule (risk taking), or min-max deviations (Aissi et al. 2009 p. 427; Artigues et al. 2013 p. 178; Scholl 2001 p. 101, 124,135ff.). In this context, scheduling problems under uncertainty often seek to comply with aspiration or satisfaction levels with a predefined probability to reach the defined objective value. Often, robustness measures are jointly considered or composited to hedge against parameter variations (Aissi et al. 2009 p. 427; Demeulemeester and Herroelen 2009 p. 52f.). The variance and standard deviation of a sample or of a complete data set are measures of the dispersion of data and are calculated as follows:

$$\boldsymbol{s^{*2} = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu)^2} \qquad (3.1)$$

(empirical variance),

$$\boldsymbol{\sigma_{X^*}} = \sqrt{\boldsymbol{s^{*2}(X)}} \tag{3.2}$$

(empirical standard deviation),

$$\boldsymbol{\sigma^2} = \boldsymbol{VAR}\ (\boldsymbol{X}) = \frac{\mathbf{1}}{\boldsymbol{N}} \sum_{\boldsymbol{i=1}}^{\boldsymbol{N}} (\boldsymbol{x_i} - \overline{\boldsymbol{x}})^{\mathbf{2}} \tag{3.3}$$

(variance if the sample is a complete inventory),

$$\boldsymbol{\sigma_X} = \sqrt{\boldsymbol{\sigma^2}} = \sqrt{\boldsymbol{VAR(X)}} \tag{3.4}$$

(standard deviation if the sample is a complete inventory).

The μ-σ criterion combines both measures mean μ and standard deviation σ into a single preference function $\phi(z_j) = \mu(z_j) + q * \sigma(z_j)$ where $q = -1$ is applied in the case of risk averse decision makers (Scholl 2001 p. 52). Often, a reduced variance of the objective value come along with a certain optimality loss, which is addressed by the μ-σ criterion if $q \neq 0$. The Laplace rule is risk neutral and chooses the strategy with minimum expected project makespan of all scenarios. The maxi-min-rule (or mini-max rule) is risk averse and chooses the optimum strategy of the most unfavorable scenario. The maxi-max-rule is risk taking and chooses the optimum strategy of the most favorable scenario. A hybrid form of maxi-min and maxi-max rules is the Hurwicz criterion, depicting a linear combination of both with optimism parameter $\lambda \in [0,1]$. The absolute or relative Savage-Niehans criteria (mini-max-regret rules) are risk averse and prefer strategies with the minimal maximum deviation from the optimal objective value of all scenarios. If a strategy has an absolute mini-max-regret of zero, it is the total optimality-robust solution (Scholl 2001 p. 138). If probabilities of occurrences for scenarios are known, other decision rules apply like Bayes rules (expectation criterion), variance criterion, expectation-variance criterion, fractal criterion or aspiration criterion (Scholl 2001)[20].

[20] For further information see (Daniels and Kouvelis 1995) for the absolute deviation robust scheduling (ADRS) Problem.

Further quality robustness measures are the expected makespan (= share of optimum objective values of a strategy in all uniformly distributed scenarios) and the service level (= project completion probability) (Demeulemeester and Herroelen 2009 p. 52).
Solution robustness is defined as the insensitivity of activity start times of a schedule to variations of input data (Hazir et al. 2010 p. 634; Herroelen and Leus 2005) or to disruptions (Gören and Sabuncuoglu 2008; Hazir et al. 2010; Van de Vonder et al. 2008). Or, it can also be defined as the difference between the baseline schedule and the realized schedule and measured by the weighted sum of the differences between their respective activities' start times (Schatteman et al. 2008 p. 14).
Similarly, stability describes the independence of a plan or schedule from environmental changes or input data (Herroelen and Leus 2005 p. 291f.; Schatteman et al. 2008 p. 14; Scholl 2001 p. 102,109). Therefore, it is often synonymously used with solution robustness (Schatteman et al. 2008 p. 13).
Further robustness categories are feasibility robustness, information robustness, planning robustness or nervousness and evaluation robustness. These robustness types are shortly described here for comprehensiveness according to (Scholl 2001 pp. 104–108), but are of no further interest in this research contribution. Feasibility robustness depicts the property of a plan or schedule to be applicable in every scenario. A total feasibility robust plan is stable and a relative feasibility robust plan is called flexible. Also, if changes of the plan do not affect the objective value negatively, a plan is flexible. If prolongation or capacity exceeding are considered via penalty costs, this criterion might be dropped. Information robustness describes the insensitivity of a plan to information quality and quantity at planning stage. An information robust plan or schedule can be recognized if planning with only some of the best possible information results in no degradation of other robustness criteria or objective values. Planning robustness describes the characteristics of a decision, plan or schedule made in $t = 0$ to be optimal without the necessity of adaption during subsequent project stages until the end

of the project. Adaptions can occur due to information updates and can mainly affect the temporary decisions (nervousness) but also the (partially) realized decisions e.g. via implementation of alternative activities. One possible measure of planning robustness or nervousness is the POSI measure (position change of activities) (Elkhyari et al. 2004). Evaluation robustness depicts the insensitivity of the ranking of schedules according to decision makers' preferences.

The relevant robustness criteria and the desirable ratio[21] of stability and flexibility vary between projects and depend on the decision context and the risk preferences. Risk averse decision makers are interested in robust planning and thus employ flexibility only if it contributes to protection in unfavorable scenarios (Scholl 2001 p. 94). In scheduling, makespan and cost are common and reasonable objectives that are used in robustness measures to evaluate the expected probability that project is completed in time (Van de Vonder et al. 2005, 2006a, 2008) or in the cost range (Aissi and Roy 2010 p. 94). Other robustness measures can include as total slack, free slack, (weighted) average slack, weighted slack, slack utility or dispersion of slacks in schedules (Hazir et al. 2010). Others consider the percentage of potentially critical activities or project buffer size (Hazir et al. 2010) as well as machine busy and repair times, total tardiness and total flow-time early and late floats or stability radius (Gören and Sabuncuoglu 2008 p. 70). For further information on robust scheduling see section 3.3.3.

Robustness can protect against unforeseen high-impact events, which is important in building deconstruction e.g. as reliable probability estimation of disruptions, contaminations or other delaying events is extremely difficult (Aissi et al. 2009 p. 427). Most important objective in deconstruction projects is the compliance with the predefined project deadline. Thus, quality robustness seems to be the most important robustness measure in deconstruction project contexts. Moreover, in deconstruction project planning and execution, flexibility of schedules

[21] For robustness tradeoffs in scheduling see (Van de Vonder et al. 2005, 2006a).

and resource assignments can be of great usefulness due to the adaptability to future developments like the finding of hazardous materials, pending new legislation or weather conditions. As schedule adaptions might result in increased cost (storage costs, contractual penalties, set up costs) a solution robust schedule is desirable in deconstruction contexts. But as deconstruction projects often need to comply with the contractual due date or deadline, schedule adaptions might be necessary with the possible consequence of additional costs. Thus, in deconstruction projects both quality robustness as well as also stability (solution robustness) is important robustness measures compare schedules.

3.2.5 Types uncertainties and their representation in modeled processes

As several types of uncertainties are influencing models, investigating the impact of different uncertainties on the decision process and the decisions is important for robustness analyses (Bertsch 2008 p. 6). Sources of uncertainties in a modeled process can be differentiated into three categories that are depicted in Table 3-3: data or parameter uncertainty, preferential uncertainty with respect to risk or uncertainty (including ‘subjectivity‘, ‘imprecision‘) and model form uncertainty (including framework conditions, system boundaries and results) (Basson 2004; Bertsch 2008; Comes 2011 p. 20).
Data or parameter uncertainty is related to input data or parameters and it is sometimes further subdivided into scenario uncertainties (Lloyd and Ries 2007 p. 162). Preferential uncertainty is related to the introduced (subjective) risk preferences of decision makers. Model form uncertainty is related to the type, structure, boundaries and results of a model. However, as model uncertainty (resp. ignorance) is inherent in every model and is hardly quantifiable, this research contribution will restrict to considering data uncertainty and to describing model boundaries. Data uncertainty can be described by fuzzy or stochastic distributions or scenarios, while preferential uncertainty is strongly advised to be treated

parametrically or with sensitivity analysis (Bertsch 2008; Morgan and Henrion 1990) (see section 5.2.5). Thus, data uncertainty (this section) and risk preferences (section 3.2.3) are described in more detail.
The classification and examples (see Table 3-3) used here might not be exhaustive and might not include all pertaining uncertainties but will be sufficient to depict major uncertainties related with building deconstruction. General uncertainties and project risks might be included by other general project management approaches such as PMBoK.

Table 3-3: Classification of uncertainties exemplary in deconstruction-related context[22]

Data or parameter uncertainty	Preferential uncertainty	Model form uncertainty
• Empirical quantities (e.g. input data of potential upstream models) with aleatoric and epistemic uncertainty • Measurement quantities	• Weighting of alternatives • Risk preferences	• Changing project scope • Not-modelled parameters and uncertainties (e.g. weather conditions)

In literature, the major concepts of uncertain data are differentiated into (a) variable data, (b) fuzzy data and (c) variable fuzzy data (Herroelen and Leus 2005; Rommelfanger 2007 p. 1892; Viertl 2003) and are described in the following:

Variable or random data can be represented through stochastic distributions with known or estimated distribution parameters that e.g. may lead to Monte-Carlo simulated realizations of the random variable (Schatteman et al. 2008). Donath et al. use this method to calculate retrofitting costs of existing buildings (Donath et al. 2010). Schatteman et al. generate activity durations for a construction project (Schatteman et al. 2008). Figure 3-5 shows main methods of distribution estimation of sample data in literature. While parametric estimation methods are suitable for larger samples, non-parametric estimation methods are

[22] According to (Basson 2004; Bertsch 2008; Comes 2011 p. 20).

adequate for estimating the distribution of small scale samples (Reuter 2009, 2013). Fuzzy data represent inexact, vague, linguistic or fragmentary information (Rommelfanger 1993; Zadeh 1965) by both convex (Möller and Beer 2004) and non-convex (Reuter 2008) fuzzy sets that are represented by possibility distributions (= membership functions) (Reuter 2013). Mainly modeled information in fuzzy sets are linguistically described properties, possibility of occurrence, logically modelled truth content, fuzzy numbers or intervals of measurements (Reuter 2013) and gradually modeled memberships of hierarchical systems (Rommelfanger 1993). Advantages of fuzzy modeling of control and decision processes are a more flexible adaptability, the relatively high stability compared to mathematical models (Rommelfanger 1993) and reduced information requirements on probability distributions. To generate membership functions of fuzzy sets, the following types of information can be utilized[23]:

- Heterogeneous measurement values can be fuzzy-clustered to generate gradual memberships of the measurements to subsets (Reuter 2011, 2013 p. 193).
- (Linguistic) expert opinions are transformed into numeric values and linear trapezoidal membership functions, if no other information is available (Herroelen and Leus 2005; Möller and Beer 2004; Wadhwa et al. 2009). The advantage of including expert opinions into the membership functions is that subjective perception can be integrated into a model (Möller and Reuter 2007; Reuter 2013; Rommelfanger 1993).

[23] Further specific procedures to create a membership function can be found in (Reuter and Schirwitz 2011).

- Variable data of a small sample can be transformed into a histogram to determine the distributions' parameters by an least square adaption (Möller and Beer 2004; Reuter 2013) [24].
- Hybrid variable fuzzy data (a sample with fuzzy elements) are modeled as realizations of a fuzzy random variable (Möller et al. 2007; Reuter 2013) with deduced fuzzy expectation and expected fuzzy-intervals.

In literature, most research focuses on PERT and CPM techniques where most authors transform the fuzzy scheduling problem into crisp scheduling by applying either alpha-cuts or a defuzzification technique (Masmoudi and Hait 2013).

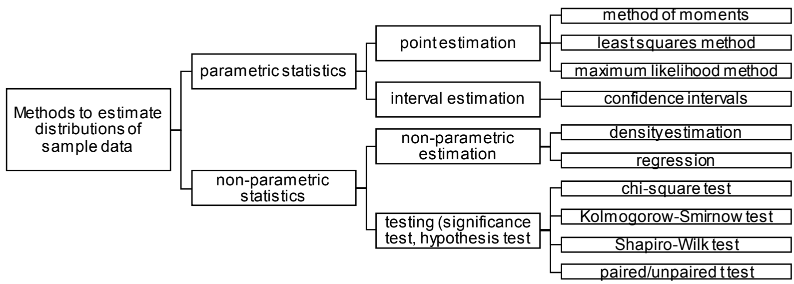

Figure 3-5: Types of inductive statistical estimation methods to estimate distributions of sample data[25]

Literature reveals a large number of different and sometimes conflicting scenario definitions, characteristics, principles, and methodological ideas (Bradfield et al. 2005). Scenarios are a powerful, convenient and natural way to represent uncertainty and uncertain future developments regard-

[24] This procedure is both suitable for convex and non-convex fuzzy sets (Möller and Beer 2004; Reuter 2013), but can be influenced by normalization and the width of the histogram classes. For convex and non-convex fuzzy set approaches see e.g. (Möller et al. 2007; Möller and Reuter 2007; Reuter 2009).

[25] According to (Benesch 2013; Reuter 2013; Viertl 2003).

less of their likelihood via the assignment of discrete plausible values to model parameters (Aissi et al. 2009 p. 427; Comes 2011 p. 30; Dembo 1991 p. 63; Merz 2011 p. 148). But also, in multi-stage cases scenarios are defined as a set of possible future sequences of outcomes or realizations (Birge and Louveaux 2011 p. 152). In the context of risk management, scenarios include a potential cause, the occurrence of the risk event and its impact (Girmscheid and Busch 2014 p. 65). In the further course the second scenario definition is used.

Scenario construction is differentiated into analytical (model-based, literature-based) and intuitive (knowledge-based) approaches (Comes 2011 p. 31f.). Usually, three parameter values are assumed in scenario construction: the expected or most likely value, the optimistic and the pessimistic value (Merz 2011 p. 56). Often, also preferences are attached to scenarios (desirability of particular paths) as preferable futures (Comes 2011 p. 30). To analyze specific project risks or the desirability or preference of scenarios, scenario planning can be applied to identify a normal or most likely case, as well as best/optimistic and worst/ pessimistic scenarios (Wengert and Schittenhelm 2013 p. 39). If probabilities can be assigned to scenarios, a probability dominance of scenarios can be calculated (Scholl 2001 p. 50) and less probable scenarios can be eliminated with the aim to fulfill predefined aspiration levels or risk thresholds of decision makers. But, if a Monte-Carlo simulation of scenario probabilities occurrences is applied, the number of scenarios can multiply (Wengert and Schittenhelm 2013 p. 39). Otherwise, if no probabilities of scenarios are available, clustering, selection and pruning rules need to be performed to reduce the number of potential scenarios to facilitate decision making (Comes 2011 p. 211ff). Or, the probability of scenarios can be assumed. Also, assumptions on equally distributed scenarios are possible due to the “law of the insufficient reason” based on Bernoulli for assuming another distribution (Scholl 2001 p. 55).

Main advantages of scenarios are that they can model discrete uncertainties when probability distributions are not known and when the revealing scenario or realization is not known beforehand. However, the generation of a multitude of scenarios increases the amount of information that decision makers need to process and take into account (Comes 2011 p. 37f.). The use of scenarios can even exacerbate the decision makers' problem, when scenarios are not accompanied by further guidance or analysis tools (Comes 2011 p. 37f.).

3.3 Project scheduling and resource capacity planning methods under uncertainty

Quantitative models and methods to support project scheduling has been the subject of research since the late 1950s and the literature in the field is extensive (Demeulemeester and Herroelen 2009 p. 2). Project scheduling approaches often focus on finding efficient solutions under complete information, deterministic conditions and a static environment (Artigues et al. 2008 p. 191). But, real projects are often subject to uncertainties that arise from work content, resource capacities and availabilities or project networks (Elkhyari et al. 2003 p. 1; Hazir et al. 2010 p. 634; Herroelen and Leus 2005). Deconstruction projects often are to be planned and executed under time or cost pressure and are subject to constrained resources, incomplete information and uncertainty. Thus, in the following, methods of operative project planning methods are described and reviewed that enable optimal scheduling of projects under uncertainty[26].

Scheduling deals with the optimal allocation of activities on resources meeting precedence relations and resource-constraints. This optimal allocation aims mostly at a time-minimal objective (minimal project duration), but can also pursue a cost-minimal objective (minimal project

[26] For further information on scheduling under uncertainty see e.g. (Artigues et al. 2008; Herroelen and Leus 2005; Pinedo 2011; Weglarz 1999) and for relationships between decision making models under uncertainty see Birge and Louveaux (Birge and Louveaux 2011 p. 87ff.). For a review of project scheduling under uncertainty, the reader is referred to (Demeulemeester and Herroelen 2009 p. 2) and (Herroelen and Leus 2005) for further relevant books and review papers on project scheduling.

budget), a revenue-maximal objective (maximal net present value) or other quality criteria. Rigid and flexible planning can be differentiated, either leading to a single baseline plan or to multiple plans for different potential developments e.g. via scenario or decision trees (Scholl et al. 2003 p. 11f.). The usual scheduling process results in a baseline schedule that includes all activity start and finishing times and fulfils several functions (Demeulemeester and Herroelen 2009 p. 1; Herroelen and Leus 2005 p. 291). The baseline schedule is very important as it is used to procure and allocate resources, to identify peak and low resource demands, to evaluate project performance and for transparency to communicate milestones at (external) project partners and staff (Aytug et al. 2005 pp. 88–91; Van de Vonder et al. 2006b p. 26). This especially occurs in multi-project settings (like for decision makers in the deconstruction industry) where a baseline schedule is used to communicate milestones or time windows along the supply chain and with the related project stakeholders such as clients, subcontractors or authorities (Demeulemeester and Herroelen 2009 p. 1). According to (Herroelen and Leus 2005 p. 291) there are three ways to incorporate uncertainty in the baseline schedule generation: either without any baseline schedule (type I), or deterministic scheduling without anticipation of variability and reactive corrections (type II) or with proactive scheduling and management decisions (type III). During project execution, dynamic scheduling policies, reactive scheduling, management decision or sensitivity analyses are possible. In project planning, deterministic and stochastic scheduling can be differentiated. Depending on the process to be modeled and the available data on activity duration variations, foreseen or unforeseen activities and their durations and resource demands either deterministic or stochastic approaches can be applied. “The majority of publications in the extensive literature on resource-constrained project scheduling focus on a static deterministic setting […]” although “in the real world, project[s] may be subject to considerable uncertainty” (Demeulemeester and Herroelen 2009).

During project execution a project (and its schedule) might be subject to uncertainty resulting in schedule disruptions, activity prolongations or truncations from expected durations, additional or omitted activities as well as varying resource demands or availability (Artigues et al. 2008 p. 203). In real projects, uncertainty is prevalent and as the project develops, additional knowledge is acquired changing the type and quality of information available (information updates) and offering new possibilities to (re-)assess and evaluate alternatives (Comes 2011 p. 37f.; Pender 2001). Thus, project scheduling under uncertainty is a multi-stage problem, where consecutive decision are made, when new information becomes available (Kall and Wallace 2003 p. 304).[27] These decision points (stages) are time instants in a project where at least one activity can be scheduled (Herroelen and Leus 2005) or after new information reveals. Decisions can be differentiated into first-stage and later-stage decisions. First-stage decisions are made before action is taken, activities are performed or events occurred. Later-stage decisions might change previous decisions after actions or events (Birge and Louveaux 2011). However, for a better understanding both static (single-stage) and dynamic (multi-stage) approaches and their impact on project scheduling are described in the following. Static, single stage scheduling restricts to one planning stage and plans a project based on initial available information over the whole planning horizon (Göbelt 2001). Later incoming information and risks cannot enter or revise the decision or strategy. Thus, the strategy resulting from single stage stochastic scheduling is not flexible and not adequate for real project planning problems (Göbelt 2001). The development of multi-stage or multi-period programming is based on (Dantzig 1955). Dynamic, multi-stage scheduling[28] includes a recursive formulation of activity dependencies over several stages or planning periods and the calculation of expected objective values of sets of actions or alternatives. Also, decisions are made at different stages

[27] See (Kall and Wallace 2003 p. 304) for the discussion on two-stage scheduling problems.
[28] For further information see (Birge and Louveaux 2011; Kall and Wallace 2003).

based on the particular information known at that time (Domschke and Drexl 2007 p. 159). Multi-stage scheduling is necessary when decisions from previous periods are linked to today's or future decisions (Birge and Louveaux 2011 p. 417). In this context, decisions are exploiting only "new information" to determine if an activity is scheduled at the current decision point. This dynamic change in information differentiates (a) affirmation or falsification of assumptions, (b) improvement of information on probability distributions and (c) determination of events. Result of the multi-stage RCPSP is a strategy that depends on the realizations of uncertain parameters of previous stages (Göbelt 2001 p. 71), and thus is a recursive, dynamic problem.

Literature on operational project planning differentiates activity-based versus location-based approaches (Henrich and Koskela 2006 p. 1), that either model activities explicitly or implicitly by their occupation of locations. Activity-based scheduling is performed with classical methods of Critical Path Method (CPM), Metra Potential Method (MPM), General Activity Networks (GAN), Program Evaluation and Review Technique (PERT) or Graphical Evaluation and Review Technique (GERT) (see Table 3-4)[29], while location-based scheduling use Line-of-Balance, Vertical-Production-Method or Time-Location-Matrix Model methods (Henrich and Koskela 2006 p. 1). Other approaches, such as lean project management are also shortly reviewed. Main distinctions between activity-based approaches are fixed (CPM, MPM, PERT) (Golenko-Ginzburg and Gonik 1997, 1998) or flexible (GAN, GERT) precedence constraints (Kellenbrink and Helber 2013; Neumann 1999) and respective project structure as well as deterministic (CPM, MPM, GAN) or stochastic (PERT, GERT) activity durations. CPM and MPM are common methods to plan activities with deterministic duration and precedence relations. PERT is a scheduling method including a certain amount of risk, since it considers esti-

[29] See also (Munier 2014 pp. 33–37) for further characteristics, advantages and disadvantages of CPM and PERT.

mates for every task duration or cost (Munier 2014 p. 3). PERT method is based on deterministic precedence relations (Elmaghraby 2005 p. 308), but can include fuzzy or stochastic activity durations. Fuzzy PERT considers minimum, expected and maximum durations of each activity and transforms them into triangular (or hexagonal) fuzzy sets (Munier 2014 p. 3). Then, like in CPM, time buffers are calculated via forward and backward passes with fuzzy summation and subtraction. Prerequisite is the known upper bound of project makespan $C_{max,UB}$. Stochastic PERT depicts optimistic (a_i), most likely (m_i) (modal value) and pessimistic (b_i) estimations of activity durations (Nickel et al. 2014 p. 166) e.g. via beta distributions with predefined parameters r and q. Then, the mean duration of each activity is calculated with

$$\boldsymbol{\mu_i} = {}^{\boldsymbol{1}}/_{\boldsymbol{3}}\,(\boldsymbol{a_i} + \boldsymbol{m_i} + \boldsymbol{b_i}) \tag{3.5}$$

and used for forward and backward passes. Although GAN and GERT methods considered all activities in the project network, they do not necessarily schedule all activities in their simulations and thus are not suitable for deconstruction project scheduling. Thus, in the following the focus lies on PERT scheduling due to its capability of representing uncertainties under deterministic precedence relations. The functionalities of CPM, MPM, GAN and GERT methods are widely described in literature, e.g. in (Corsten et al. 2008 p. 124; Neumann 1999; Nickel et al. 2014 p. 151; Zimmermann et al. 2006)[30].

The mentioned methods CPM, PERT, GAN and GERT are applied to plan time, activity durations and project makespan, but do not consider resource constraints or schedule protection (Corsten et al. 2008 p. 176ff;

[30] Although Markov chains can depict stochastic processes via system status, they have been neglected here due to many disadvantages to classical scheduling methods: state-nodes instead of activity or event nodes are represented, precedences are not applicable due to the memoryless stochastic process and only the initial critical path can be described neglecting other critical paths that may result from activity delays or unexpected events.

Demeulemeester and Herroelen 2009 p. 4). However, if activity-based scheduling under resource constraints is required, problems are formulated in resource-constrained project scheduling problem (RCPSP), where scheduling and capacity planning is performed simultaneously to fulfill objectives (Brucker et al. 1999; Chtourou and Haouari 2008; Corsten et al. 2008 p. 177; Demeulemeester and Herroelen 2009 p. 4; Hartmann and Briskorn 2010; Herroelen and Leus 2005). RCPSP with fixed and acyclic precedence network is the extension of PERT by an resource and capacity planning with restricted resources (Corsten et al. 2008 p. 176ff).

Table 3-4: Deterministic and stochastic project scheduling approaches under different assumptions[31]

	Single valued expectations	**Multi valued expectations**
Deterministic precedence (all activities scheduled)	Deterministic network planning technique (e.g. CPM, MPM)	Deterministic network planning technique with stochastic parameters (e.g. PERT)
Non-deterministic precedence (fraction of activities scheduled)	Stochastic network planning technique with deterministic parameters (e.g. GAN)	Stochastic network planning technique (e.g. GERT)

RCPSP are subject to research since the late 1960s (Mahmoudoff 2006), and have been extended for and applied in many fields (Brucker et al. 1999; Herroelen and Leus 2005). Therein, activities are defined that require resources such as renewable resources (machines, equipment or staff) and non-renewable resources (cost) and that need to be scheduled under resource constraints such as defined time frame (deadline) or activities' precedence[32]. The binary decision variable x defines the

31 According to (Corsten et al. 2008 p. 124; Nickel et al. 2014 p. 151).

32 For the handling of other resources in project scheduling see e.g. (Schwindt and Zimmermann 2015a pp. 177–230).

optimal starting (or ending) point of all activities (schedule) in the planning horizon. Activities' precedences describe the logical or technological sequence or parallelism of activities in an adjacency matrix. Precedence constraints are often described in Activity-on-Arc (AoA) (usually CPM), Activity-on-Node (AoN) (usually MPM) or Event-on-Node (EoN) (usually PERT) networks (Corsten et al. 2008 p. 122; Nickel et al. 2014 p. 150; Weglarz et al. 2011). During RCPSP planning, both time and resource constraints as well as resource capacities are met (Elkhyari et al. 2003 p. 1). Single-mode and multi-mode project scheduling problems are a generalization of job shop scheduling problems (Brucker 2004; Brucker et al. 1999 p. 15; Kolisch 1995; Schultmann 1998 p. 141). This problem class is NP complete[33] (Neumann et al. 2002 p. 153; Schultmann 1998 p. 141f.).

A morphological overview on activity-based scheduling problems and their variants is presented in Table 3-5 classified by their modelling approach, objectives, number of projects, number of modes, constraints and problem class. Profound descriptions and reviews of the classical RCPSP and common variants can also be found in literature, e.g. in (Brucker et al. 1999; Hartmann and Briskorn 2010; Herroelen and Leus 2005; Kao et al. 2006; Neumann et al. 2002; Pinedo 2011; Schwindt and Zimmermann 2015a; b; Zimmermann et al. 2006).
Main objectives of projects are makespan minimization, cost minimization or quality maximization. Objectives can be classified into time-related, cost-/resource-related, or robustness-related (quality-, or performance-related) (Weglarz et al. 2011). The latter expressed in adherence to due dates or deadlines, resource levelling, project progress performance, cost/makespan deviations or minimal sensitivity to schedule perturbation (robustness) (Hartmann and Briskorn 2010; Hazir et al. 2011; Weglarz et al. 2011) (see Table 3-5). E.g. in the robustness maximization approach of Chtourou and Haouari (2008), the RCPSP is first

[33] See section 3.4 for a characterization of deconstruction projects and section 4.4.4 for solvability and solution procedures.

solved with minimum project makespan C_{max} and then robustness with twelve surrogate robustness measures is maximized while keeping C_{max} under a threshold value to avoid the bi-objective dilemma (Chtourou and Haouari 2008 p. 185). For both problems, they apply a priority-based heuristic.

If multiple objectives are addressed, often conflicting effects occur such as the time-cost tradeoff[34] or stability-makespan tradeoff (Van de Vonder et al. 2006a) problem. Often, multi-objective[35] problems that combine several objectives in one call for pareto-optimal respective efficient tradeoffs. Other mentioned objectives in literature are minimal or maximal time lags (earliness or tardiness), deadlines (violation not possible), due dates (violation possible at penalty costs), maximal net present value or other concepts (Hartmann and Briskorn 2010). The optimal solutions in multi-objective optimization can be found by partial ordering or domination (Deb 2010 p. 341) as well as by tradeoffs (Hazir et al. 2010; Schultmann 1998). Other specifications of the RCPSP can include (non-)preemptive activities, changing resource demands over time, setup times, workload tradeoffs (Hartmann and Briskorn 2010; Seppänen et al. 2010), multi-project[36], multi-mode ((M)MRCPSP)[37] or multi-skill[38] scheduling. And, projects under uncertainty[39] are subject to different kinds of undesirable schedule disruptions, schedule infeasibility and project delay or cost overrun (Demeulemeester and Herroelen 2009

[34] Shorter project makespan needs increased resources leading to increased cost. Vice versa, reduced cost lead to savings in resources lead to longer project completion time/makespan. For further information see e.g. (Schwindt and Zimmermann 2015a p. 621ff).

[35] Synonymously: Multi-criteria problem (Hartmann and Briskorn 2010). For more information on multi-objective project planning see (Hapke and Slowinski 2000; Masmoudi and Hait 2013; Slowinski 1981; Sprecher 1994).

[36] For more information on single and especially multi-project planning see (Herroelen and Leus 2004 pp. 1613–1616; Kao et al. 2006; Xu and Feng 2014; Xu and Zhang 2012).

[37] For more information on MRCPSP see e.g. (Hanchate et al. 2012; Ramachandra 2006; Schwindt and Zimmermann 2015a p. 445ff; Weglarz et al. 2011).

[38] For more information on multi-skill project scheduling see e.g. (Artigues et al. 2008 p. 149ff. (Chapter 9); Santos and Tereso 2014).

[39] Section 4.3.1 describes the types of uncertainties that apply in deconstruction projects.

p. 5; Elkhyari et al. 2003 p. 1, 2004; Van de Vonder et al. 2008 p. 723). To integrate and handle uncertainties and imprecise data into operational project management, several approaches were developed in recent years that are shortly presented in the following subsections: predictive-reactive scheduling in section 3.3.3, stochastic scheduling in section 3.3.1, fuzzy scheduling in section 3.3.2, and proactive-reactive scheduling in section 3.3.4.

Table 3-5: Non-exhaustive morphological box on RCPSP variants[40]

Modeling Approach	**Deterministic Programming**	**Fuzzy Programming**	**Fuzzy-Stochastic Programming**	**Stochastic Programming**		
Objective	Single	Multi				
Single time-based	Min. makespan	Min. tardiness or earliness	Min. (weighted) free float, time lags or setup times	Min. rework times		
Single resource- or cost- based	Max. resource utilization (with penalty for overuse)	Min. resource variation/ Max. resource leveling	Min. of (non-) renewable resource utilization	Min. cost (and delay penalties, or setup cost)	Max. NPV	
Single robustness-based	Min. risk	Min. perturbation of original schedule	Min. changes in resource utilization	Max. credibility at α-confidence/ membership levels		
Multi tradeoff	time<->cost	time<->resource	time<->risk	stability (late-/earliness) <-> time		
Project	Single	Multi				
Mode	Single	Multi				
Stage	Single	Multi				
Constraints						
Time/ Duration	(Non-) preemptive activities	Setup times for activities	With/without due dates or deadlines	Time-switches/ windows	Activity crashing/ shortening by additional cost	
Resources	(non-) renewable, or doubly-constrained resources	Time-dependent resource demand/ capacity	Cumulative resources	Continuous resources	Dedicated resources	Rented or internal/ external resources
Activity precedence	Logical dependencies (AND/OR/XOR nodes)	Fixed/Flexible precedence networks	Precedence networks with/without loops	(Limited) serialism/ parallelism of activities		
Quality	Robustness of schedule (e.g. measured by weighted free float)	Resource levelling	(Multi-)skills of staff	Rework time of activities		
Problem class	Linear	Nonlinear				

40 According to (Artigues et al. 2008 p. 137ff.; Brucker et al. 1999; Göbelt 2001; Hartmann and Briskorn 2010; Herroelen and Leus 2005; Kao et al. 2006; Ramachandra 2006; Weglarz et al. 2011).

Scheduling problems (RCPSP, (M)MRCPSP) can be solved both by exact and heuristic solving procedures (see also section 4.4.4) and are widely discussed in literature (Brucker et al. 1999; Herroelen and Leus 2005). The MRCPSP was firstly introduced by (Talbot 1982) and has been treated by several authors since the early 1980s and exact solution algorithms for these problems were presented by Hartmann, Drexl and Sprecher (Neumann et al. 2002 p. 146).

Location-based approaches use the methods of harmonograms or time-location matrix, line-of-balance (LOB), horizontal and vertical scheduling method, flow lines or repetitive scheduling method (RSM) to maximize resource utilization, to minimize activity disruptions or to minimize the effects of experience and learning curves (Henrich and Koskela 2006; Kenley and Seppänen 2010 p. 6). Harmonograms are a special type of Gantt charts that depict activity durations as well as their locations needed to perform the activity either graphically or in a matrix (Kenley and Seppänen 2010 p. 52). Line-of-balance graphically monitors the production rate [cumulated items per time unit] or compares it with a given production or delivery plan and evaluates deviations (Kenley and Seppänen 2010 p. 58ff.). Thus, this method is not suitable to create schedules but to monitor resource utilization and project progress. Horizontal and vertical scheduling considers the horizontal (working zones on a story) and vertical (stories in a building) characteristics of jobsite production processes in construction projects (Kenley and Seppänen 2010 p. 69). This approach was extended by Thabet and Beliveau into a space-constrained, resource-constrained scheduling system (SCaRC) for construction projects (Thabet and Beliveau 1997). This approach has two steps: Firstly, activity duration and production rates are determined to schedule the activity on resources. Secondly, work and storage areas are defined. In both planning stages, production rate changes or right-shifting rules are applied when resource or location constraints cannot be respected. However, this approach does not consider multiple execution modes and resource demands of activities, it

does not optimize the resulting schedule nor does it consider uncertainties or scenarios (Thabet and Beliveau 1997).
Flow lines depict the flow of resources through jobsite locations. This concept is linked to the previously mentioned line-of-balance concept, but locations are represented on the Y-axis instead of produced unites (Kenley and Seppänen 2010 pp. 71–73). Location-based management system (LBMS) is an extension of flow lines that creates similar sized subprojects on a location-breakdown structure and depicts the resulting flow line for the whole project (Kenley and Seppänen 2010 p. 73). For each subproject (respective team), optimal sequences of activities are determined leading to the total project makespan. The repetitive scheduling method (RSM) is an iterative approach to calculate detailed CPM schedules for each location to find the “critical path” in the flow lines and to minimize project makespan (Kenley and Seppänen 2010 p. 89). The LBMS integrates CPM into flowline scheduling that manages tasks and locations by workflow and productivity rates of staff teams (Büchmann-Slorup 2012; Seppänen 2009; Seppänen et al. 2010). Also, LBMS is both a planning and a controlling tool with periodic information updates (progress reporting). Comparably to RCPSP or CPM, in LBMS activities are subject to resource and precedence constraints. But, LBMS considers locations explicitly, while RCPSP might include locations as renewable resources by adequate constraints with differing renewal cycles. The main difference between the classical CPM and LBMS consists in specific resource continuity constraints and thus in the possibility of reducing workflow interruptions and increasing productivity by omitting setup time after interruptions (Büchmann-Slorup 2012; Lowe et al. 2012). Büchmann-Slorup examined the criticality in LBM and combined activity-based and location-based scheduling approaches, but without considering uncertainties (Büchmann-Slorup 2012). However, practitioners report 10% schedule compression through LBMS without risk increase (VICO Software 2014).
Newer approaches in production and construction management are based on lean principles contrived and documented by Womack et al.

(Womack et al. 1990). Numerous works of Ballard, Howell, Kenley, Koskela, Seppänen and others transfer lean principles (continuous workflow, pull principle, responsibility etc.) to project management in building construction with cooperative and interactive elements to improve project planning (e.g. Last Planner System) (Ballard and Howell 2003; Kenley and Seppänen 2010; Seppänen et al. 2010)[41]. In lean project scheduling, several project schedules are created with different aggregation and timely focus. First, a framework time scheduling is created with milestones. Then, sub schedules of project stages are created by the project team. This is followed by a preview and a weekly plan with classified activities that should, can, or will be done (Howell and Ballard 1994). The categories imply either all activities or all activities whose preconditions are met (e.g. resource availability or previous activities) or all activities that are planned in the weekly plan. However, despite its advantages in practice regarding improved project organization and well-informed staff, is not clear how uncertainties are considered in lean project management. Variability of upstream processes is buffered in lean management (Howell and Ballard 1994), however the consideration of foreseen and unforeseen uncertainty is not clear. As deconstruction work in small and medium sized projects is mainly done by a single contractor, the organizational approach of lean construction management to reduce delays or cost deviations is less relevant than an activity-based or location-based approach (Seppänen et al. 2010). Thus, literature on lean construction principles and management are neglected here in favor of mathematical scheduling models. Nevertheless, lean principles might be interesting to extend current approaches by timely or spatial coordination of several contractors in large projects of gutting, retrofitting, renovation or deconstruction projects e.g. in nuclear power plants.

[41] For more information on lean construction, lean management or last planner system see e.g. (Ballard and Howell 2003; Lowe et al. 2012; Seppänen 2009; Seppänen et al. 2010).

3.3.1 Stochastic scheduling

Methods of stochastic programming[42] are applied to generate decisions if parameters are unknown at the time of decision, but can be described via probability distributions or related statistical values of arithmetic mean, variance, standard deviation or correlations of parameters[43]. Stochastic scheduling[44] generates schedules and comprises the optimization of expected functionals or objectives (Birge and Louveaux 2011 p. 87) with (partially) known random or stochastic input parameters, activity preemptions, project disruptions, mode selections, resource demands or constraints. Also, risk measures can be included in the objective function or in constraints (Birge and Louveaux 2011 p. 84) such as:

- Integration of coefficients and penalty terms into the objective function through
  - expected objective value or,
  - integration of weighted risk aversion coefficients with respect to deviations from the expected objective value or,
  - definition of a minimal/maximal objective value as upper/lower boundary (Göbelt 2001; McCarl and Spreen 1997).
- By modeling uncertain or time-variant constraints (Dembo 1991 p. 63) through
  - variable resource availabilities over time,
  - variable resource demands and activity modes over time,
  - expected resource demands values,
  - variable work content (Ramachandra 2006; Tereso et al. 2004).

[42] For further information on stochastic programming see (Birge and Louveaux 2011; Kall and Wallace 2003) and for combined fuzzy-stochastic approaches see e.g. (Mohan and Nguyen 2001; Rommelfanger 2007).

[43] Probabilities of occurrence might either be generated via expert assessments or statistical data (Girmscheid and Busch 2014 p. 64) or be assumed uniformly distributed.

[44] For further information on stochastic scheduling see (Elmaghraby and Morgan 2007; Golenko-Ginzburg and Gonik 1997; Klerides and Hadjiconstantinou 2010; Neumann 1999; Pinedo 2011 p. 349–374 (Part II); Rafiee et al. 2014; Schwindt and Zimmermann 2015b p. 753ff).

In stochastic scheduling problems, main objective is the minimization of expected makespan $E(C_{max}(\prod(d)))$ over a class of policies (Herroelen and Leus 2004 p. 1602, 2005 p. 292). Based on the available information, a scheduling policy $\prod(d)$ decides at the decision points project start ($t = 0$) and the completion times of activities j ($t \in (0; T]$) about a feasible set of activity start (or ending) times x_j (Herroelen and Leus 2005 p. 292).

Realizations of the uncertain parameters have to be assumed before an optimization can be performed or a decision can be made. Then, Monte Carlo approaches simulate activity durations, stochastic disruption modeling and stochastic time constraints. And, different assumptions on the number of activities (all= MPM, PERT; fraction= GAN, GERT) or on single or multi valued expectations are possible (see also Table 3-4) (Corsten et al. 2008 p. 124ff).

Aside from stochastic input parameters, also stochastic (flexible) precedence relations (GAN, GERT)[45] between activities and single or multiple stages can be considered (Koberstein 2013; Morgan 2007). This allows a more realistic modeling of the decision-making process. Multi-objectives (tradeoff problems), multi-stages and multi-modes can also be included, but at the same time further complicate the problem (Herroelen and Leus 2005 pp. 292–296). „While deterministic multi-period optimization yields decisions for all periods, a stochastic approach only yields policies or strategies" (Wallace and Fleten 2003). Mainly discussed policies in literature are: priority policies (Chtourou and Haouari 2008 p. 187), early start policies, (linear) pre-selective policies, activity-based policies and pre-processing policies (Demeulemeester and Herroelen 2009 p. 42; Möhring et al. 1984, 1985) as well as proactive policies (Deblaere et al. 2011a).

Major drawback of stochastic scheduling models is that they do not generate a baseline schedule, but create strategies or policies prior to

[45] For a comprehensive description on stochastic networks (GERT, GAN) see e.g. (Corsten et al. 2008 p. 226ff.; Kellenbrink and Helber 2013; Neumann 1999).

project start that plan the activities during project execution (Demeulemeester and Herroelen 2009 p. 5,39; Herroelen and Leus 2005 p. 292; Möhring et al. 1984, 1985). Another drawback in the multi-stage case is an exponential increase in problem size per stage (Birge and Louveaux 2011 p. 417).

For sequential, multi-stage decision making, four main dynamic programming methods are applicable: scenario trees, decision trees, event trees, and influence diagrams (Comes 2011 p. 323ff.; Göbelt 2001 p. 71; Kall and Wallace 2003 p. 124ff., 153).
In stochastic scenario trees (=EMV), nodes (realizations, states) and arcs (decisions) are assigned with direct or indirect probabilities and depict the possible future path of development of the uncertain parameters (Göbelt 2001 p. 71). Thus, they allow sequential decision making (Kall and Wallace 2003 pp. 124–129)[46], as every path from the root to a leaf of the decision tree can be interpreted as a scenario (=sequence of states) (Birge and Louveaux 2011 p. 152; Göbelt 2001 p. 71; Scholl 2001 p. 57). Scenario trees assume that future developments are independent from already made decisions. In deconstruction projects several potential scenarios are possible and the realized scenario reveals itself in the course of the project, rather than a set of changing and successive scenarios (with probabilities) that is modelled with scenario trees. Scenario trees are rather not applicable here, because in building deconstruction projects the proactive, anticipated description of future project states is quite difficult. Rather, the uncertain, unknown building configuration can be anticipated in scenarios (in the sense of an information gap), which cannot be represented by scenario trees. Furthermore, necessary stochastic information on the probability of the scenarios is needed, but is not available in deconstruction projects.

[46] Thus, stochastic optimization might be sometimes interpreted as an extension of scenario analysis (Göbelt 2001 p. 74).

To construct the different scenarios in each stage and over several stages, also a stochastic decision tree can be used as they are able to consider future status (information status) and information changes/updates and later decisions that depend on own previous decisions (Scholl 2001 p. 58). Stochastic decision trees extend scenario trees by decision nodes (see Figure 3-6) and suppose that future states and developments depend on previous decisions (Scholl 2001 p. 58). Decision trees allow conjoint consideration of sequential decision making and uncertainties (Bertsch 2008 p. 149). In chance nodes, probabilities of the alternatives are assigned and the outcomes of the events are revealed to the decision maker (Comes 2011 p. 325). With backward recursion using Bellman's principle of optimality, the decision tree can be resolved to receive an expected objective value for $t = 0$ (Bertsch 2008 p. 150). It can also be combined with decision makers preferences (Kall and Wallace 2003 pp. 124–129). Prerequisites of decision trees are a limited number of realizations and finite discrete distributions on the scenarios which may be assumed as equally distributed if information is lacking. The redundancy in decision trees might be met and avoided with adequate modeling (Göbelt 2001 p. 72).

Decision trees with fixed periodic stages (decision points) might be applicable in deconstruction projects, as the previous decisions (schedules) in the project do influence the realized scenario (revealing of new building information of building configuration) by the resource allocation and the sequence of the activities. But as this method is only applicable for a limited number of decisions (Kall and Wallace 2003 pp. 121–122) and is limited to small problems (Comes 2011 p. 324), it is less suitable for multi-mode scheduling with many alternatives and numerous stages. Furthermore, the a priori determination of the different stages and their length might be difficult (Bertsch 2008 p. 150). And, with respect to this application case the proactive consideration of future information updates and decisions in a decision tree would greatly increase the number of scenarios and thus the computational effort that is already very high (and is expected to grow near insolvability when realistic cases are applied). And, decision trees do not depict dependencies and information flows (Shachter 1986). Thus, decision trees are not applied here. Related influence diagrams[47] complement decision trees by dependencies and conditionality of decisions (Bertsch 2008 p. 149), but are less adequate to depict scheduling problems. Thus, this approach is not further considered here.

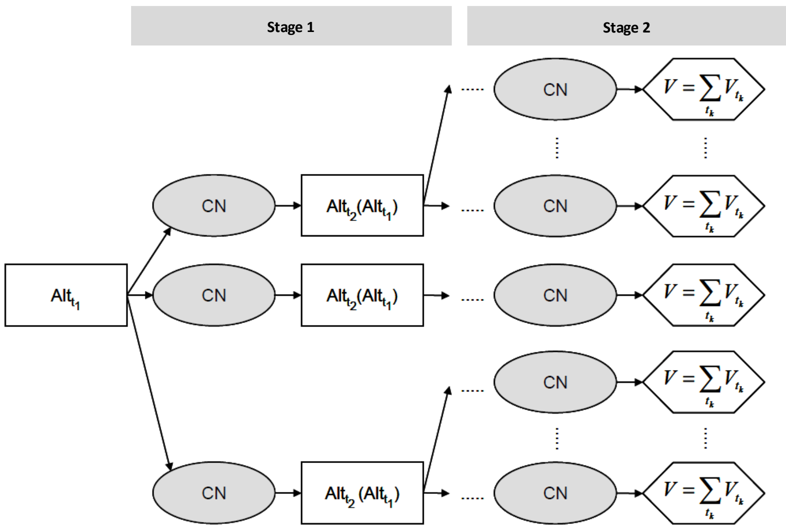

Figure 3-6: Decision tree with chance nodes (CN) (representing possible scenarios or actions) and decision nodes (representing alternatives Alt of selected strategies or actions) and the resulting value V[48]

Event trees are similar to decision and scenario trees, but are able to cope with continuous decision variables (Kall and Wallace 2003 p. 134). As continuous decision variables are not required in scheduling, event trees are not further considered.

[47] For further information see (Bertsch 2008 p. 148; Comes 2011).
[48] According to (Bertsch 2008 p. 149).

Also, time-based decomposition method of rolling wave (horizon) planning[49] is related to decision trees as it considers strong temporal interdependencies (Pinedo 2011 p. 403; Scholl 2001 p. 138f.). Rolling wave planning successively schedules only the next activities in each stage s that are to be planned in the predefined planning horizon and establishes a new schedule for the next stage after the previous schedule was realized (Pinedo 2011 pp. 403–407; Scholl 2001 pp. 32–33; Scholl et al. 2003 p. 2). After a defined period, the procedure is repeated for the next planning horizon. The rolling wave (horizon) method considers a limited planning horizon of its sub schedules and reschedules in the next stage the remaining, not yet realized activities and additional activities relevant for the new, partly overlapping planning horizon (Scholl 2001 pp. 33–34). Some approaches realize this concept with time-overlaps, others include a fixed number of activities per planning period or only the activities with current release dates during planning period (Pinedo 2011 p. 404). The rolling wave method initially plans with known or assumed activity duration and resource demands (Sethi and Sorger 1991) and is capable of also including new information that was generated during previous project stages and forecasting costs into the planning process. Rolling wave planning belongs to the category of 'wait-and-see' concepts and considers only timely interdependences within the planning horizon of each sub schedule.

Main advantage of this method is the anticipation of future developments (system state, forecasts) beyond the actual planning horizon and the possibility of reaction at a later stage (Scholl 2001 p. 139) and the consideration of timely interdependences (Scholl 2001) similarly to predictive-reactive scheduling (see section 3.3.3). This results in more feasibility robust project schedules (Scholl 2001 p. 140). Also, the limited planning horizon in each stage enables decision makers to plan long or continuous projects with often hardly quantifiable future uncertainties,

[49] This concept is often also described as a stochastic dynamic approach. For further information see (Scholl 2001; Scholl et al. 2003; Sethi and Sorger 1991).

but at the same time this method does not reveal the overall optimal solution. Main drawbacks are the fact, that sub scheduling might neglect information necessary for a 'best' total project schedule and increased planning nervousness (less planning robustness) (Scholl 2001 p. 139). The difference of rolling wave to dynamic planning is that the rolling wave considers finite planning horizons in a wait-and-see manner while dynamic planning reasons backwards based on complete stochastic information over the whole project planning horizon. To implement the concept of rolling wave in deconstruction projects, adequate variable or fixed decision points (stages) would have to be defined, information of the project status would have to be collected and the (un)expected events would have to be estimated. Application of this method especially seems promising for long-lasting projects, such as the deconstruction of nuclear power plants, although the major drawback of the non-optimality of the project schedule needs to be taken into account.

Markov chains can also be used to describe project scheduling problems and to generate optimal policies (Choi et al. 2004). In this types of models, it is difficult to describe the project state and a comprehensive modeling of project states results in a high number of nodes and computational complexity (Choi et al. 2004 p. 1041). But, homogeneous Markov chains are not able to depict parallel activities that are processed simultaneously. If a project is modeled with this method, only the critical path can be modeled. But, if the critical path changes due to prolonged activities, the modeled process has to be remodeled with changed transition probabilities. Thus, this method seems not suitable for deconstruction project modeling.

As stochastic problems often are hardly solvable, they are often replaced by two types of simplifications (Birge and Louveaux 2011 p. 163). Either, compensation problems are used where uncertain variables are replaced by their expectation value or several scenario-based deterministic problems are created and solved, followed by a combination of the multiple solutions (Birge and Louveaux 2011 p. 163; Klerides and Hadjiconstantinou 2010). Instead of applying stochastic or fuzzy distributions, the use of expected parameters, single values or prognosis of parameter values' development over time lead to deterministic (solvable) optimization models (Corsten et al. 2008; Scholl 2001 p. 30). And, as PERT/ GERT are network planning techniques with stochastic activity durations without/ with flexible precedence networks, they are hardly solvable analytically (Domschke and Drexl 2007 p. 236). Therefore, stochastic network planning methods often are solved by simulation (Domschke and Drexl 2007 p. 236). However, compared to dynamic scheduling this is seen rather disadvantageous (Elmaghraby 2005), e.g. because, "odd and special situations are often automatically excluded from consideration as only the expected values – the normal cases – are considered" (Wallace and Fleten 2003). The expected value of perfect information (EVPI) and the value of the stochastic solution (VSS) measure the quality of such compensation problems (Scholl 2001 pp. 77, 80, 195). The EVPI indicates maximum amount a decision maker would be ready to pay in return for complete (and accurate) information about the future, while VSS describes the potential benefit from the stochastic solution over the deterministic solution (Birge and Louveaux 2011 p. 163ff.). Main disadvantage of stochastic scheduling is the fact that major prerequisite for stochastic network planning is the knowledge about parameter distributions (Birge and Louveaux 2011 p. 87; Hazir et al. 2010 p. 634). If (especially risk averse) decision makers do not have distribution information as in the case of most deconstruction projects, robust scheduling is more appropriate (Hazir et al. 2010 p. 634) than stochastic network planning.

3.3.2 Fuzzy scheduling

Fuzzy scheduling or fuzzy-stochastic scheduling is applied, when a lack of historical data does not allow statements on activity durations' distribution or to determine probabilities of occurrence of scheduling parameters (Rommelfanger 1993; Zadeh 1965). On the one hand, fuzzy preference profiles can represent flexible precedence constraints, on the other hand activity durations are described by fuzzy sets that substitute deterministic values or stochastic distributions (Dubois et al. 2003 p. 231). So-called fuzzy sets include minimum, expect and maximum parameter values that can be complemented by further values of a certain membership level such as the core, the 0.5 level cut with unsurprising values and the support of the boundary areas (Dubois et al. 2003 p. 238; Rommelfanger 1990). Also, both convex and non-convex fuzzy sets can be used (Möller and Reuter 2007; Reuter 2009). When fuzzy or stochastic modelling is applied, objectives are complemented by α-confidence or membership levels, expected values, (standard) deviations or (weighted) means. To solve the fuzzy project scheduling problem, possibility theory is consulted with crisp interval or six-point representation (Masmoudi and Hait 2013) to create a fuzzy or fuzzy-stochastic schedule with minimal project duration, minimal schedule risk or maximal worst case schedule performance. Then, each crisp scheduling problem is solved separately and schedules of the separate problems have to be defuzzified or jointly evaluated to provide the decision maker with a recommendation. Another difficulty is the determination of critical activities, latest starting times and floats (Dubois et al. 2003 p. 231).

Fuzzy scheduling with fuzzy set activity durations often proves to be a powerful tool for modeling weak data (Pan et al. 2001; Schultmann 2003; Xianggang and Wei 2010; Xu and Feng 2014). It seems appropriate when probability distributions and historical data are lacking, so that activity durations (and other uncertain parameters) have to be estimated via small data samples (such as building catalogues, most frequent building types), expert knowledge, linguistic or qualitative information, often in an non-repetitive or unique setting (Herroelen and Leus 2005; Pan et al. 2001).Major fields of fuzzy project scheduling research were devoted to fuzzy PERT and CPM (Dubois et al. 2003; Masmoudi and Hait 2013). For more information on fuzzy scheduling see (Dubois et al. 1993, 2003; Hapke and Slowinski 2000; Zadeh 1965) and on fuzzy MRCPSP see

(Hapke and Slowinski 2000). As both fuzzy and stochastic concepts are transformable into each other (Dubois et al. 1993), newer concepts combine both complementing approaches (Mohan and Nguyen 2001; Rommelfanger 2007; Xu and Feng 2014; Xu and Zhang 2012).
Main advantages are the possible integration of linguistic information and expert opinion in mathematical models. Major drawbacks are the limited solution space if only six crisp scheduling problems are created from the six-point representation. In deconstruction scheduling problems, the integration of expert opinion and the transformation of linguistic information into the scheduling model seem promising. But, when the required data for the six-point representation is not available, the method is not applicable and results might not easy to understand to decision makers. Schultmann considers fuzzy activity durations in deconstruction project planning (Schultmann 2003), but neglects other uncertainties like building element materials and volumes that have a considerable influence on project scheduling, makespan and cost.

3.3.3 Predictive-reactive scheduling

"The term predictive-reactive scheduling has been introduced in the literature to denote the case of a predictive baseline schedule that is developed prior to the start of the project and that may be updated during the project execution phase." (Herroelen and Leus 2004 p. 1600; Vieira et al. 2003 p. 44) In literature, predictive-reactive scheduling is described as the generation of repairing strategies after a baseline schedule has become unfeasible (Herroelen and Leus 2005 p. 290). Baseline schedules are project execution plans that are generated prior to project execution (Hazir et al. 2010 p. 635). Reactive scheduling includes revising, repairing or re-optimization of a baseline schedule after unexpected events according to predefined strategies with the aim of minimizing perturbation of schedule or resource allocation (Artigues et al. 2008 p. 191ff.; Deblaere et al. 2008 p. 2, 2011b p. 308). However, schedule repairing based on predefined rules creates rather poor results as it does not allow resequencing (Herroelen and Leus 2004 p. 1610). Predictive-reactive scheduling approaches do not consider variabilities or other uncertainty when generating the initial baseline schedules, but apply various rules and heuristics during project execution phase to revise and correct the schedule when an unexpected event such as activity preemption, project disruption or resource unavailability (such as machine break-down) occurred (Chtourou and Haouari 2008 p. 184; Gören and Sabuncuoglu 2008 p. 67; Herroelen and Leus 2005 p. 290)[50]. Several rules have been developed to adapt infeasible schedules to receive feasible ones: schedule repair (e.g. right-shifting rule), activity crashing, neighborhood search in a set of similar schedules, or full rescheduling[51] (Artigues et al. 2008 p. 191ff.; Herroelen and Leus 2004 p. 1610ff). E.g. Deblaere et al. (2008) consider taboo search to identify lower and upper bounds followed by a single-mode branch-and-bound algorithm and a neighborhood search for 'better' modes that will increase the already found baseline objective value (Deblaere et al. 2008 pp. 4–30; Herroelen and Leus 2005 p. 291). Deblaere et al. (2011) determine a project execution policy and a vector of predictive activity starting times so that the simulated policy execution costs are minimized (Deblaere et al. 2011a p. 315). Also, reactive single-mode RCPSP approaches are devoted to static and dynamic priority-based sampling schemes that generate several feasible schedules from which the best can be selected (Demeulemeester and Herroelen 2009 p. 162f.). For this purpose, remaining activities are either scheduled as early as possible or according to railway scheduling at the earliest that the start time of the baseline schedule. Although exact solution procedures exist, they suffer from high computational efforts and are not applicable on larger problem instances (Demeulemeester and Herroelen 2009 p. 162).

[50] For an overview on predictive- reactive scheduling the reader is referred to (Deblaere et al. 2008, 2011b, Herroelen and Leus 2004 p. 1602ff, 2005; Van de Vonder et al. 2007a).

[51] For an overview on rescheduling the reader is referred to (Vieira et al. 2003).

As this scheduling type is not proactively considering expected uncertainty during project planning at t=0, it is only partly adequate for answering the research question (see section 1.2) and model requirements (see section 4.1). But, as it allows schedule adaptions during project execution, approaches of this type are interesting with respect to the integration of dynamic schedule changes and thus some reactive elements are also applied in this research contribution.

3.3.4 Proactive-reactive (robust) scheduling

Risk-averse decision makers are often interested in hedging against risk of some events or lack of information that results in worse system performance, especially in unique problems or projects (Daniels and Kouvelis 1995 p. 364). But, classical approaches fail to recognize that when jobs with uncertain attributes are scheduled and do not consider decision makers risk preferences. Thus, proactive-reactive (robust[52]) scheduling[53] aims at the generation of a robust baseline schedule that incorporates a certain degree of anticipation of potential variability (Herroelen and Leus 2004 p. 1602) or of potential disruptions (Demeulemeester and Herroelen 2009 p. 47; Gören and Sabuncuoglu 2008 p. 67) and at protection of the baseline schedule (Artigues et al. 2008 p. 191, 203ff.; Demeulemeester and Herroelen 2009 p. 39; Van de Vonder et al. 2008 p. 732) so that the objective value (makespan) or the schedule itself is minimally impacted by uncertainties. Such baseline schedules should absorb the need of new scheduling or rescheduling to a certain degree and should have at the same time acceptable objective values. In the case of schedule infeasibility when the built-in protection fails during the execution of the project, reactive (repairing) strategies are applied (Deblaere et al. 2008 p. 3; Demeulemeester and Herroelen

[52] For the definition of 'robustness' see section 3.2.4.

[53] For further information see (Demeulemeester and Herroelen 2009; Herroelen and Leus 2004, 2005; Kouvelis and Yu 1997; Nikulin 2006; Pinedo 2011 p. 485ff (Chapter 18); Scholl 2001; Schwindt and Zimmermann 2015b p. 865ff) and for a graphical overview see (Demeulemeester and Herroelen 2009 p. 6 (Table 1.1.))

2009 p. 4). As at the moment of project planning it is not apparent which scenario will materialize but at the same time an optimization is pursued, a robust planning is the best way (Gebhard 2009 p. 34).

Research showed that the combination of proactive and reactive scheduling techniques lead to significant stability improvement in the planning nervousness, with only moderate (hence acceptable) increases in schedule makespan (Artigues et al. 2008 p. 211; Van de Vonder et al. 2006a, 2008 p. 723). And, a proactive or proactive-reactive approach seems to be more effective than a purely reactive one (Van de Vonder et al. 2007b).

In literature, proactive-reactive scheduling was virtually void until recently (Artigues et al. 2008 p. 209; Van de Vonder et al. 2008 p. 723). Only few studies proposed measures to assess the robustness of project schedules (Hazir et al. 2010 p. 635). However, in the last years the number of works in this area increased (Artigues et al. 2013, 2015; Chtourou and Haouari 2008; Daniels and Kouvelis 1995; Deblaere et al. 2011a; Demeulemeester and Herroelen 2009; Gören and Sabuncuoglu 2008; Hazir et al. 2010, 2011; Kouvelis and Yu 1997; Lambrechts et al. 2008; Nikulin 2006; Schatteman et al. 2008; Van de Vonder et al. 2006b; b, 2008). In proactive and reactive single-mode RCPSP some work has already been done, but literature on proactive-reactive scheduling policies in multi-mode RCPSP was "virtually void" (Deblaere et al. 2008 p. 2) and is still very limited (Demeulemeester and Herroelen 2009 p. 164; Godinho and Branco 2012 p. 561). The problem of coping with activity duration variability has been addressed in (Van de Vonder 2006; Van de Vonder et al. 2007a, 2008) and the problem of uncertainty with respect to resource availability has been addressed by (Deblaere et al. 2008 p. 2; Lambrechts et al. 2008). But, "to anticipate a deconstruction procedure, numerous different objectives in environmental, technical and economic means have to be taken into account. […]" (Schultmann 2003).

Main concepts are based on resource redundancy/buffering, on buffering/idle time insertion into feasible baseline schedules to fulfil specific robustness criteria (Demeulemeester and Herroelen 2009 p. 38,48;

Mehta and Uzsoy 1998; Schatteman et al. 2008; Van de Vonder et al. 2005, 2006a, 2008), on multiple schedules (Herroelen and Leus 2005 p. 298) and on uncertain data on activity duration or resource availability represented as scenarios (Artigues et al. 2013; Mulvey et al. 1995).[54] In the multi-mode case, some sources propose rescheduling, mode switching or increase of resource availability (Zhu et al. 2005) or exact and heuristic repairing (Deblaere et al. 2011b). Others describe starting time policies or threshold policies (Godinho and Branco 2012 p. 555) to adapt a schedule to new information or current project status, but without considering renewable resources. Godinho and Branco also indicate, that their presented adaptive policies are better than non-adaptive policies that are based on the expected deterministic problem (Godinho and Branco 2012 p. 557).
Research also addresses random project disruptions (Gören and Sabuncuoglu 2008; Hazir et al. 2010; Van de Vonder et al. 2008) and their impact on schedule and objective value as well as potential measures for schedule protection. Elkhyari et al. construct a model of the potential perturbations of the initial problem and insert additional activities (Elkhyari et al. 2004). Hazir et al. (2010) consider disruptions caused by uncontrollable factors in a robust discrete time/cost trade-off problem with multi-modes under a project deadline and cost minimization (Hazir et al. 2010 p. 641). They find that project buffer size is an appropriate robustness measure to protect a schedule against disruptions (Hazir et al. 2010 p. 641).

Another widely-known approach is the theory of constraints or critical chain scheduling of Goldratt that iteratively creates a schedule based on latest start times and resource conflict resolutions (Herroelen and Leus 2004 p. 1603). The theory of constraints implements planning of projects or plants via throughput or bottleneck optimization of production scheduling and control which is accompanied by a buffer insertion and

[54] For a review on recent approaches see (Chtourou and Haouari 2008 p. 184f.)

management (Goldratt 1997). “For a single-project environment, the methodology seems practical and well thought-out. […], but it imposes extra constraints on project execution in order to facilitate makespan estimation, […]. It obscures extra scheduling options, and enforces a rigid focus on what was critical at the start of the project but may no longer be crucial after a certain lapse of time.” (Herroelen and Leus 2004 p. 1616). The theory of constraints also proposes buffer insertion to increase schedule quality-robustness[55] (Chtourou and Haouari 2008 p. 184; Goldratt 1997) although it suffers from serious oversimplification (Herroelen and Leus 2004 p. 1605f.). Furthermore, the elimination of due dates in critical chain management (Herroelen and Leus 2004 p. 1604) is a unrealistic issue in the face of strict time constraints in deconstruction projects. As buffer insertion assumes known activity durations or activity duration distributions, it is not applicable in this case and thus is excluded from further considerations. Also, some approaches proactively cope with uncertain activity durations or uncertain renewable resource availability aiming at a solution-robust baseline schedule, but future research is needed (Artigues et al. 2008 p. 210f.; Van de Vonder et al. 2006a p. 234f.), e.g. based on simulation to compare different schedules in the generation of solution and quality robust schedules under resource constraints (Herroelen and Leus 2004 p. 1609).

Scenario-based approaches are rather seldom in literature yet due to the difficult identification of discrete activity attributes and the construction of realistic scenarios with adequate activity durations.
Klerides and Hadjiconstantinou describe the inherent uncertainties via a set of discrete scenarios with a probability of occurrence and with their respective activity durations (Klerides and Hadjiconstantinou 2010 p. 2131). In this approach, the scheduling problem is formulated as a MRCPSP with budget constraints that is solved for each scenario (path). However, they assume that each scenario constitutes a path that cannot

[55] Optimality-robustness is often synonymously used (Scholl 2001 p. 102).

be changed later on (via structural changes) and only activity prolongations are considered. In a second stage, the realization of activity durations is considered (Klerides and Hadjiconstantinou 2010 p. 2132f.). They also provide a capable of solving procedure that copes with many large and hard test instances in reasonable computational time using modest memory requirements (Klerides and Hadjiconstantinou 2010 p. 2139).
Artigues et al. describe a scenario-based mini-max absolute regret[56] robust RCPSP (AR-RCPSP) where decision makers cannot assign with confidence probabilities to possible activity durations (Artigues et al. 2013 p. 176). Thus, possible realizations of the activity durations are represented as scenarios. In this model, the aim is to find an earliest-start policy that minimizes the maximum absolute regret over all scenarios. Artigues et al. (2013) develop solution procedures for this problem and found that this problem is computationally overly demanding even for medium-sized problem instances.
Also, the tradeoff problem between project makespan (quality robustness) and schedule stability (solution robustness) was addressed and proved to be a promising approach (Van de Vonder et al. 2006a) to receive a robust schedule. Protected activity durations or inserted idle times are used to create a baseline schedule and minimize the maximum earliness or lateness which equals the summed up deviation of expected activity durations from baseline schedule or the assigned risk.

3.4 Characterization of deconstruction projects

Due to long building lifecycles and changing users' or energetic, health and environmental requirements, buildings are renovated, retrofitted, remediated or modernized by generations of users, residents and proprietaries. When buildings cannot economically be adapted to new requirements or when onsite another type of use in the form of a new

[56] The absolute regret is also sometimes referred to as worst case robustness metric (Herroelen and Leus 2004 p. 1609).

building/construction or open space is planned, proprietors often decide to deconstruct or replace the building. Due to a buildings' uniqueness and its unique framework conditions, construction, change and also deconstruction measures can be characterized as and are organized in projects[57] (Abdullah et al. 2003). Thus, since the deconstruction of a building or infrastructure has project characteristics, operative project planning and management methods can be applied.

The buildings in question undergo deconstruction (and replacement) processes, often in spatially limited sites of dense urban areas and with limited resources available. Deconstruction is a co-production or joint production problem (Spengler 1998) where several building elements, building materials and waste streams are 'produced' from a complex product (building) in different rates depending on the applied resources and techniques.

In building deconstruction, different constrained renewable resources (machines, staff) are used in different execution modes to perform so-called jobs (activities) like separation and deconstruction activities that are followed by crushing, sorting and loading activities. These jobs might also be performed several times due to reworks e.g. in the case of contaminations. Furthermore, technical or organizational precedence relations of activities have to be respected. Generally, job shop scheduling approaches of operations research depict scheduling problems of site fabrication which are applicable for construction, retrofit and deconstruction projects (Schultmann 1998 p. 141f.). Job shop scheduling problems plan each job j on m machines where each job has its own predetermined route (Pinedo 2011 p. 14), with precedence constraints, makespan minimization and under resource-constraints ($Jm \mid prec \mid C_{max}$)[58]. It initially seems to be the most appropriate scheduling problem type for this application case (Schultmann 1998 p. 141f.). But since deconstruction belongs to the category of site fabrication, there are

[57] For a definition of 'project' see DIN 69901-5:2009-01 or ISO 21500:2013-06

[58] Notation according to (Brucker et al. 1999 p. 5; Neumann et al. 2002 p. 22).

rather different modes how jobs can be performed than predetermined routes on a machine environment. And, simultaneous technique selection and resource planning is required to address the deconstruction scheduling adequately. Thus, in this case a multi-mode project scheduling problem ($MPS \mid prec \mid C_{max}$)[58] with renewable resources under resource constraints (MRCPSP) and with zero-lag finish-start precedence relations seems promising. Figure 2-7 shows the deconstruction degrees and precedences in detail, while Figure 2-8 shows the simplified building element-related precedences relations in a three-storey deconstruction project based on (Schultmann 1998).

Furthermore, deconstruction project activities can be described by nodes in an activity-on-node network and all nodes of the networks have to be visited (executed) once. As GERT and GAN methods only visit a subset of all nodes of the network need, these methods are not adequate to describe the problem. And, although the stochastic network planning techniques of GERT and GAN seem promising for deconstruction planning under uncertainty, these methods are inadequate due to several reasons: (1) Often, in deconstruction projects there are no probabilities of occurrence assignable to building elements or alternatives. (2) Reduction methods of stochastic networks are needed to enable mathematical analysis (Corsten et al. 2008 p. 234). (3) To solve GERT networks that have been reduced to exclusive-OR networks (EOR), still a high computational effort is needed allowing only few decision points (Corsten et al. 2008 p. 234).

Deconstruction projects can be divided into four major project phases: (1) pre-deconstruction phase including auditing and planning, (2), deconstruction preparation phase, (3) deconstruction phase, and (4) post-deconstruction phase including sorting, recycling, disposal and controlling (see also section 2.3). This research contribution and the following literature review in section 3.5 restricts to the consideration of the planning phase containing pre-deconstruction phase including auditing and deconstruction planning of phases (2) and (3) together with the consideration of project makespan and cost.

The objective of the responsible stakeholders of deconstruction projects is either makespan minimization or cost minimization or both depending on the type of building, the urgency or the preference of the responsible parties. Major foci in deconstruction of buildings are the minimization of project makespan and project cost. To plan change measures in existing buildings, buildings have to be audited previously. In new construction projects, this step is replaced by site inspection of the ground. Then, the project and its activities are defined by an architect, planning engineer or the building owner himself. After the definition of the measures, the operative project planning begins and fully relies on the previously audited building information. Thus, project performance and the amount of change measures (and partly project risks) strongly depend on the quality of the initially acquired information. Often, the acquisition of building information of existing buildings is associated with expensive equipment and great acquisition and modelling effort of skilled staff (see section 2.3.1). The following paragraph provides a detailed literature overview on project planning of deconstruction projects[59].

3.5 Literature review on project management, risk management and decision support in deconstruction projects[60]

Despite a vast amount of general project planning and scheduling literature, literature in project or risk management of deconstruction of buildings and infrastructures is limited to a relatively small number. Main approaches can be separated into analytical hierarchy process (AHP), optimization (RCPSP) and mass flow simulation models.

[59] See also sections 2.3, 3.1.2 and 0 or the following excursus or (Girmscheid and Busch 2014; Sunke 2009) or standard literature like (Berner et al. 2014) for project and risk management in construction.

[60] Parts of this literature review have been published previously in (Volk et al. 2015a; b).

Figure 3-7 shows the existing literature in the three main research areas of deconstruction, project management and scheduling and risk management. A comprehensive review of project management and scheduling literature (OR) can be found in section 3.3. Risk management is addressed in section 3.2.2 and existing deconstruction approaches are considered and reviewed in this section. Figure 3-7 shows that there are several works in all three areas, however, the intersection set of all three areas is still void.

Table 3-6 shows a more detailed overview on the main reviewed deconstruction project planning approaches and their characteristics, which are also described in detail in the following. Also, Table 3-6 shows the model scope and the most important uncertainties in deconstruction project planning: uncertain activity duration, uncertain activity cost and insufficient documentation of building element mass and material.

Existing literature in deconstruction project management either focused on building auditing (Raess et al. 2005; Rentz 1993; Rentz et al. 1994a; b, 1998a; b; Schultmann 1998), on surveying deconstruction activity durations and cost (Rentz 1993; Rentz et al. 1994a; b, 1998a; b; Schultmann 1998), on defining disassembly groups (Rentz 1993; Rentz et al. 1994a; b, 1998a; b; Schultmann 1998), on debris sorting and (re-)processing (Rentz et al. 2002; Seemann 2003) and on debris recycling (Andrä et al. 1994; Nicolai 1994).

Models based on analytical hierarchy process (AHP) or the related non-hierarchical multi-criteria decision-making (MCDM) offer rather qualitative decision support in deconstruction projects on aggregated level. Abdullah et al. (2003) and Anumba et al. (2008) provide project planning and decision making support in deconstruction via hierarchical multi-criteria decision-making (MCDM) approach to develop a tool for adequate or ‘best’ demolition techniques selection in deconstruction projects (Abdullah et al. 2003; Abdullah and Anumba 2002a; b; Anumba et al. 2008). Their approach creates a ranking according to the highest benefit per cost ratio and estimate the demolition cost for the whole project according to the highest ranked demolition techniques per activity (Abdullah et al. 2003; Anumba et al. 2008). Toppel (2004) also uses a MCDA utility analysis of alternative mode selection for deconstruction projects to identify suitable and cost-minimal deconstruction techniques (modes) in compliance with the decision makers preferences (weighting in MCDA) (Toppel 2004 p 142). This allows the analysis of a complex solution space according to a multidimensional set of criteria. This approach does not consider operative activity scheduling or sequencing, but only multiplies building element volumes and cost factors of the selected modes, to calculate total project cost and similarly to estimate project makespan. Uncertainties are not considered explicitly in the approach.

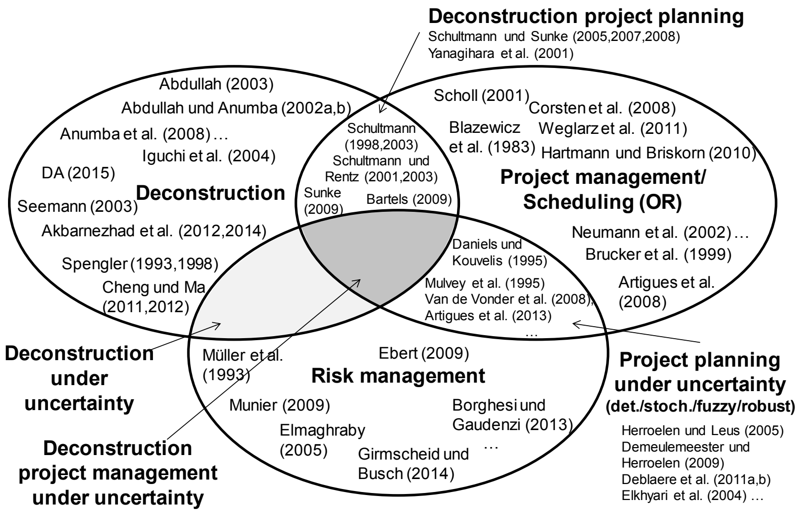

Figure 3-7: Literature overview in the three main research areas

Operative optimization models use the previously introduced methods of scheduling and capacity planning reviewed in section 3.2.5 such as CPM, MPM, PERT or RCPSP. Main approaches of deconstruction planning

and scheduling optimization stem from Schultmann, Rentz, Spengler and Seemann offer operative decision support on simultaneous resource and capacity planning to minimize deconstruction project makespan or total project cost. Schultmann (1998) formulates and solves a deterministic multi-mode RCPSP with renewable resources and presents application cases in deconstruction projects. However, this model has some limitations such as the absence of non-renewable resources (e.g. limited project budget), no capability to depict different environmental framework conditions, uncertainties or future development (Schultmann 1998 p. 111). This central optimization-based work on deconstruction project planning includes a building auditing support and an optimization tool for building deconstruction project planning in MS ACCESS 1998 (Schultmann 1998, 2003; Schultmann et al. 1997; Schultmann and Rentz 2001, 2003). It is based on pre-measured building element dimensions and user assumptions regarding building element material and quality. Applied optimization concepts from Schultmann and Rentz (Schultmann 1998; Schultmann and Rentz 2001) focus on the minimization of makespan in fixed precedence networks with deterministic parameters and deterministic activity durations and cost. Although the consideration of uncertainties is indispensable when it comes to deconstruction scheduling of old and often undocumented buildings, there is only a single approach considering uncertainties in deconstruction scheduling. Based on his former works, Schultmann (2003) formulates a fuzzy scheduling approach, that is divided into six crisp RCPS problems with optimistic, more or less expected and pessimistic values with different fuzzy set membership values (1, ε, λ) (Schultmann 2003). However, this approach does not cover all uncertainties decision makers are confronted with fuzzy due dates, fuzzy capacity constraints, uncertain composition of the components or fuzzy precedence relations (Schultmann 2003) which are impractical or in the need of defuzzification.
As an extension to the works of (Schultmann 1998), Seemann describes simulations of sorting, processing and recycling techniques with the focus on cost minimization (Seemann 2003). Furthermore, Schultmann

and Sunke (2007) extended the approach of (Schultmann 1998) by additionally considering the recycling options of each building element and the related energy-saving effects due to different deconstruction activities (Schultmann and Sunke 2007a). Another approach of Schultmann and Sunke describes a problem formulation of multi-project scheduling problems (Schultmann and Sunke 2007b) that allows decision makers to plan their resources onto their project portfolio. This approach connects the strategic and the operative viewpoint in deconstruction project planning. However, it does not present an example or application case and does not consider uncertainties or computational effort to solve this at least NP-hard problem. Another extension of Schultmann and Sunke (2006) includes the recovery rate of building elements and materials into the project planning (Schultmann and Sunke 2006). This is done via reformulation of the objective function into maximization of the recovery rate of all deconstruction activities in all modes and all materials. However, this approach does not consider uncertainties at all.

Sunke (2009) describes several project planning and tour planning methods in construction and deconstruction contexts. Her models are based on RCPSP problem formulation with extensions on resource priorities (critical, neutral, uncritical resources) and rescheduling, if project changes occur (Sunke 2009). Sunke (2009) generally mentions deconstruction optimization models but stays unclear regarding their application in buildings or infrastructure or the related uncertainties (Sunke 2009). And, this approach does neither consider uncertainties explicitly, controlling or project progresses nor does the author provides practical verification of the planning approaches and model results (Sunke 2009).

Table 3-6: Literature overview in deconstruction project scheduling and focus (grey) of this contribution

		(Abdullah and Anumba 2002a; b; Anumba et al. 2008)	(Akbarnezhad et al. 2012, 2014)	(Bartels 2009)	(Cheng and Ma 2011, 2012)	(Iguchi et al. 2004)	(Schultmann 1998; Schultmann et al. 1997; Schultmann and Rentz 2001)	(Schultmann 2003)	(Schultmann and Sunke 2005, 2008)	(Schultmann and Sunke 2006)	(Schultmann and Sunke 2007a)	(Seemann 2003)	(Spengler 1993, 1998)	(Sunke 2009)	Toppel (2004)	Yanagihara et al. (2001)
Model scope	Building FM, retrofits	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-
	Building deconstruction planning	X	X	-	X	-	X	X	-	X	X	X	-	-	X	-
	Building deconstruction optimization	-	-	-	-	-	X	X	-	X	X	X	-	-	-	-
	Building recycling/ disposal	X	X	-	X	-	X	X	-	X	-	X	-	-	-	-
	Other	-	-	X°	-	X°	-	-	X*	-	-	-	X*	X**	-	X°
Uncertainties	Activity durations	-	-	(-)	-	-	-	X	X	-	-	(-)	-	(-)	-	-
	Activity cost	-	-	-	-	-	-	-	-	-	-	(-)	X	(-)	-	-
	Build. element masses	-	-	(-)	-	-	-	-	-	-	-	-	-	-	-	-
	Building element materials	-	-	-	-	-	-	(-)	-	-	-	-	-	-	-	-
	Other	-	-	(-)	-	-	-	(-)	-	-	-	-	-	-	-	-

X: considered
(-): mentioned, not considered
-: not considered
°: deconstruction of nuclear power plants
**: construction
***: recycling capacities/revenues
grey: focus

Further related optimization approaches are disassembly and fuzzy scheduling and capacity planning of complex products with uncertain activity durations (Schultmann 2003; Schultmann and Rentz 2003), with uncertain capacities and cost (Spengler 1998), or with the disassembly of electronic devices and partly related uncertainties (Schultmann and Sunke 2005, 2008; Spengler 1998). Spengler formulates a mixed-integer linear program (MILP) to solve the optimization problem for the deconstruction of complex products and compounds in general, but restricts to deconstruction and recycling cost and maximization of the marginal return (Spengler 1993, 1998 p. 61). The described example of Spengler restricts to a single-mode, cost minimization problem for the disassembly of a microwave oven which is far less complex than the deconstruction of buildings or infrastructures. Further works of Spengler in this area include approaches of the determination of the optimal deconstruction depth and the modelling of deconstruction processes via petri nets (Spengler 1998).

Bartels (2009) formulates a multi-skill bi-modal RCPSP with discounted cash flow minimization for deconstruction of nuclear power plants (Bartels 2009). Furthermore, minimum and maximum time lags and renewable, non-renewable and cumulative resources with variable resource demand for deconstruction are modeled (Bartels 2009). The MRCPSP for nuclear power plant deconstruction is formulated as a long-term project planning problem with very aggregated planning in steps of 3 month that is accompanied by a medium-term (3 years) and short-term (0.5 years) planning (Bartels 2009 p. 50). Bartels' approach restricts to the aggregated project plan, influences on the sub-plans are not intended. However, despite the long planning horizon, he does not mention uncertainties in both long-term and short-term planning problems nor does he provide solutions to integrate them. But, without further detailing he mentions a statistical software that estimates activity duration, resource demand and cost based on radioactivity or element mass (Bartels 2009 p. 114). And, Bartels only models two modes (execution with own staff via external staff) and considers activity durations

that are independent from their modus (resource-resource-tradeoff), which strongly simplifies the problem (Bartels 2009 p. 29).
Project management methods for nuclear power plant deconstruction are also presented by (Yanagihara et al. 2001) and (Iguchi et al. 2004). Yanagihara et al. describe a database model (COSMARD) that includes creation of work breakdown structure, as well as PERT scheduling with precedence constraints and cost estimation functionalities based on experience values (Yanagihara et al. 2001). Estimation values of resource demands, radioactivity doses, duration and cost are derived per building element or technical component and based on an experience database. However, uncertainties are not explicitly considered in the described model and solution procedures and parameters of the scheduling model are not concretized. Based on the COSMARD model of Yanagihara et al., Iguchi et al. describe a CAD-based system (DEXUS) that allows the deconstruction simulation of a nuclear reactor components to optimize workload, exposure dose, waste mass and cost (Iguchi et al. 2004 p. 367). The underlying schedule is automatically generated by a software, but further details on how the schedule is generated are not described (Iguchi et al. 2004 p. 369).

Mass flow simulation approaches in deconstruction project planning include works of Akbarnezhad, Cheng and Ma (Akbarnezhad et al. 2012, 2014; Cheng and Ma 2012). Akbarnezhad et al. examine a scenario-based (not activity-based) sensitivity analysis of deterministic total costs for deconstruction, transportation, reprocessing and disposal (landfilling) measures as well as of energy and carbon embodiments (Akbarnezhad et al. 2014). However, in this work different predefined deconstruction strategies similar to mode selections are enumerated for the given building configuration to solve the cost minimization problem for the transportation of the created material masses. However, the number of deconstruction strategies (#4) is relatively small and uncertainties are not considered in this approach.

Recent trends show the application shift of building information models (BIM) initially used in design processes to BIM application in retrofitting (and even deconstruction) projects. Mass flow models of Akbarnezhad, Cheng and Ma are also based on information from building information models (BIM) but consider the deconstruction of single buildings (Akbarnezhad et al. 2012, 2014; Cheng and Ma 2012). However, these works focus on the quantity takeoff, mass and cost calculation aiming at ordering the exact number of hauling trucks, calculating the demand of hauling truck frequency (Cheng and Ma 2012) and calculating the masses designated for recycling or disposal facilities. And, uncertainties and different modes are not considered. Furthermore, as there is normally very few building information available of buildings that will be deconstructed yet the use of BIM as input data in the model is quite unrealistic at this moment.
Liu et al. describe a capable web-based waste management system for trading secondary raw materials that were generated during building deconstruction projects (Liu et al. 2003). In Germany, such systems are implemented in "Bauteilbörsen". According to Liu et al., this system can be connected to a comprehensive deconstruction planning and management system (Liu et al. 2003). However, this approach does neither include project scheduling approaches nor on how to include risk or uncertainty.
Furthermore, related waste quantification and management for construction (Li and Zhang 2013) or for deconstruction (Akbarnezhad et al. 2012, 2014; Cheng and Ma 2012; Liu et al. 2003) that refrain from considering uncertainties. On the one hand, existing models consider scheduling with deterministic deconstruction activity durations (Chen and Li 2006; Li et al. 2002; Schultmann 1998; Schultmann and Sunke 2007a; Seemann 2003). On the other hand, fuzzy activity durations are applied (Schultmann 2003; Schultmann and Rentz 2003; Spengler 1998). Although some approaches name (Schultmann 1998) and consider (Schultmann and Sunke 2007a) a multi-objective deconstruction problem, the objective of minimizing makespan remains the principal aim. Related

approaches are not or only partly transferable to the deconstruction planning problem under uncertainty due to the complexity of buildings, the different applicable modes and the technical constraints that have to be considered.

3.6 Excursus: Construction and retrofit project management approaches

In the following, a short overview on construction and retrofitting project management approaches is given. Construction project management is a wide field and it is related to this work as its project conditions are somewhat similar to deconstruction projects. However, construction projects are not focus of this work and thus only promising approaches are addressed shortly. For a comprehensive overview on construction project management see main works in literature (Berner et al. 2014; Eastman et al. 2011; Girmscheid 2014; Kenley and Seppänen 2010; Sunke 2009).

To plan retrofitting projects, Donath et al. capture an existing building from scratch and calculate its retrofit costs as random variables with underlying cost distributions per activity or retrofit measure (Donath et al. 2010). A Monte Carlo simulation enables the consideration of uncertainties in cost calculation of real buildings (Donath et al. 2010), but without underlying activity-based project scheduling. Donath et al. simulate project cost depending on a digital representation of the building and a Monte Carlo simulation on a known probability distribution of activity costs.

Due to complexity and large budgets in construction projects, research on and application of project management methods is more common. Xu and al. (2012) describe a scheduling problem with discrete time-cost-environment tradeoff, with multiple modes and fuzzy project makespan that is heuristically solved (Xu et al. 2012 p. 950). Based on this work, Xu and Feng (2014) describe a fuzzy-stochastic multi-project, multi-objective, multi-mode RCPSP (MRCMPSP) for power plant construction considering uncertain activity durations, cost, quality and resource demand (Xu and Feng 2014). They formulated a hybrid model with random and fuzzy uncertainty, with uncertain (fuzzy) activity durations and fuzzy resource demands of activities (Xu and Feng 2014). Although this approach is quite extensive, it does not consider the uncertainties in building elements, the representation of information updates per project stage, a flexible precedence or robustness of results. Moreover, Xu et al. and Xu and Feng take stochastic distributions or fuzzy set on activity durations or other variables and model parameters for granted, which are not necessarily available in deconstruction projects. Thus, this approach seems not to be transferable to deconstruction project scheduling. Also, highly complex problem formulation implies a low traceability and transparency of model results for users. Nickel et al. show exemplary the application of network planning for a building construction via MPM and PERT, but refer to (Pinedo 2011) for scheduling under resource constraints (Nickel et al. 2014 p. 54ff.).

Schatteman et al. propose a proactive construction project scheduling system that identifies risk factors, groups of activities according to their risk potential and derives probabilities of occurrences of schedule disruptions and integrates them into the planned schedule (Schatteman et al. 2008). Therefore, Schatteman et al. rely on an existing risk management database that is maintained by a research institute. However, regarding the application of the approach in deconstruction projects, first an adequate risk database has to be established and maintained beyond entrepreneurial structures before the approach can be transferred.

Chen and Li transferred and extended the approach of (Abdullah and Anumba 2002a; b) by considering a multi-criteria analytical network process (ANP) to construction projects to integrate interdependences between activities to select best deconstruction alternatives (Chen et al. 2002; Chen and Li 2006). Chen and Li (2006) offer a tool for rather strategic emission management based on AHP/ANP for construction projects that assigns priorities to construction alternatives. Chen and Li (Chen et al. 2002; Chen and Li 2006) model activity emissions and environmental hazards of construction activities with optimistic, pessimistic and most likely values which is similar to fuzzy sets. Also, they use a strategic deconstruction technique (similar to mode) alternative selection (see (Abdullah and Anumba 2002a; b; Anumba et al. 2008)) via MCDA depending on criteria like structural characteristics, site conditions, demolition cost, past experience, time, and potential for reuse and recycling and combine it with activity scheduling and underlying precedence relations. Furthermore, Chen and Li developed an activity-related approach to calculate and integrate environmental impacts using a developed index in deconstruction projects and combined it with MS Project and a genetic algorithm (GA). The approach is linked to MS Project for scheduling, resource levelling and Gantt diagram creation purposes (Chen and Li 2006 pp. 33–43). Pollution values resulting from construction activities are treated as a pseudo-resource and a resource-levelling technique based von genetic algorithm is applied to redistribute pollution emissions over project time (Chen and Li 2006 p. 73). Although the main approach is deterministic, (Chen et al. 2002; Chen and Li 2006) consider uncertainties in a fuzzy data representation of environmental hazards according to experts' estimations.

Issa (2013) proclaims an activity-related risk management in construction via risk factors with impact on construction project makespan and considers rescheduling with fuzzy durations and weekly stages (Issa 2013). Similarly, Schatteman et al. examine risk factors and their impact (disruption, cost, delay) onto baseline schedules in construction projects and propose a method for robust schedule construction (Schatteman et al. 2008).

Moreover, increasingly building information models (BIM) enable and enhance operative project management methods and risk management in construction (Hartmann et al. 2012). Gu and London mention the potential application of BIM for analyses of time sequence and cash flow modelling as well as simulation, risk scenario planning and changes in work practice (Gu and London 2010 p. 998). But they also state, that current commercial products are not mature enough respectively do not provide such functionality yet (Gu and London 2010 p. 998). Hartmann et al. show the integration of traditional risk management methods into BIM via visualization of risks in time and space at an infrastructure construction project (Hartmann et al. 2012). Operative deconstruction support or management approaches through BIM is inexistent yet (Volk et al. 2014). Location-based models in construction project planning are considered e.g. (Henrich and Koskela 2006; Kenley and Seppänen 2010 p. 6) and reviewed in section 3.2.5.

This subsection demonstrates that there are numerous approaches and extensive literature in the project planning and management of construction projects. However, as deconstruction projects have another objective and have to deal with different uncertainties (e.g. expected (hazardous) materials or building element masses) and partly different framework conditions, the existing approaches in construction project planning are not directly transferable to deconstruction projects.

3.7 Summary and conclusion

In this section, a comprehensive overview on uncertainty, risk and risk management, robustness and flexibility as well as on decision makers' preferences is given. Also, several general methods to include uncertainty into project scheduling are presented. Then, a characterization of deconstruction projects and a literature overview on deconstruction scheduling is given. And, appropriateness of methods in deconstruction project scheduling is comprehensively discussed. The following paragraphs conclude the single subsections:

Section 3.1 gives relevant definitions of projects and project structures and describe project management both in general and in construction and deconstruction context. Also, project indicators and project management software are shortly addressed and reviewed. Here, "important areas for future research are the modeling capabilities of […] software packages for project management, and the resource-constrained scheduling capabilities for corresponding project scenarios“ (Trautmann and Baumann 2009b p. 632). This section is important to understand the following decision situation, the model development, the model formulation and implementation better.

Section 3.2 provides terminology on risk and uncertainties (section 3.2.1) and their management (section 3.2.2) as well as an overview on uncertainty representation. Subsection 3.2.3 gives an overview on decision makers' risk preferences, and the possible modeling of such preferences in concave, linear or convex utility functions. Also, it is discussed that in deconstruction project management risk-averse preferences prevail. Subsection 3.2.4 describes and discusses robustness criteria used in literature as well as flexibility and nervousness in the context of project scheduling and project management with respect to different risk preferences. In subsection 3.2.5, representation of uncertainties in modeled (engineering) processes and their possible integration into operative scheduling via probabilistic, fuzzy and scenario modeling techniques are described and their requirements and limitations are discussed. This section substantiates that fuzzy and scenario-based techniques are adequate measures for uncertainty representation if no probabilities of occurrences are available.

Section 3.3 depicts a classification of project planning and project scheduling methods under uncertainty and their current state-of-the-art. Activity-based and location-based scheduling is differentiated. Activity-based scheduling models consider activities explicitly; location-based scheduling describe activities implicitly by their occupation of locations. Activity-based problems with limited renewable resources (constrained over time periods) and non-renewable resources (budgeted over the whole project) resources are formulated as RCPSP with simultaneous scheduling and capacity planning (Brucker et al. 1999; Hartmann and

Briskorn 2010; Herroelen and Leus 2005; Pinedo 2011). Location-based approaches were developed for and are often applied in construction projects to increase production rates and reduce project makespan (Kenley and Seppänen 2010; Seppänen et al. 2010) and thus seem promising for deconstruction application, too. Thus, a conjoint consideration of activity-based and location-based approach where locations are considered as resources that are required for activities' execution seems promising for the application case in this research contribution. Furthermore, different project scheduling methods are presented and discussed with their advantages and limitations that explicitly consider uncertainties (mainly uncertain activity durations and cost) in different ways. Literature about project scheduling under uncertainty is extensive and publications can be divided into stochastic, fuzzy, predictive-reactive and proactive (robust) scheduling (Herroelen and Leus 2005):

Stochastic scheduling is based on distributions of scheduling parameters (e.g. activity durations in (Schatteman et al. 2008)), that are either known or can be derived from experience databases. Main drawbacks of stochastic scheduling are a lacking baseline schedule and a high computational effort of recursive multi-stage formulations. In deconstruction projects, a baseline schedule is required for staff, contractor and stakeholder communication. Also, the probability information of building configurations, scenarios or activity durations that is required for stochastic scheduling cannot be provided for most deconstruction projects. Thus, as stochastic scheduling seems not appropriate to formulate and solve deconstruction project planning problems. Also, as discussed in section 3.3.1, stochastic decision trees and rolling horizon are possible methods to represent the sequential decision making process in deconstruction projects. Decision trees allow scenario construction and inclusion of uncertainties, but this method is not capable to provide resource capacity planning and with many decision points it is computationally demanding. As continuous decision variables and conditionality of decisions are not required in scheduling, event trees and influence

diagrams are not further considered. Rolling horizon has the advantage to plan long-lasting projects (such as deconstruction of nuclear power plants), but it does not provide a total optimal objective value (makespan or cost) but rather optimized values for each stage. And, the optimal planning horizon is not easy to be defined.
Fuzzy scheduling is based on expert estimations of activity durations whereas stochastic scheduling is based on known distributions of activity durations, e.g. in (Xu and Feng 2014; Xu and Zhang 2012), but it does not consider specific project circumstances such as building elements or materials.

Fuzzy scheduling is generally possible in deconstruction project scheduling (Schultmann 2003). However, the data for the required fuzzy sets beyond a three-point representation of minimum, expected and maximum values are hard to gain and satisfaction levels of the membership function would have to be assumed for deconstruction projects. And, the building element materials which are responsible for the required resources and time demands cannot adequately be modeled.

Regarding the predictiveness, proactiveness or reactiveness of deconstruction schedules, all concepts have considerable advantages and disadvantages. Predictive-reactive approaches create a baseline schedule (predictive) with potential repairing strategies (reactive) in the case of unexpected events. However, they do not consider “known unknowns” into the baseline schedule that can be anticipated before project start e.g. such as potential deviations in the building configuration. Reactiveness includes flexibility and adaptation of a schedule after unexpected events that cannot be anticipated before. Reactive approaches only apply if the previously chosen plan becomes infeasible during project execution. In deconstruction projects, several unexpected events might happen: machine breakdown, worker illness, crack formation in neighboring houses, unexpected hazardous materials or contaminated soil that lead to project disruption and consequently to an infeasible baseline schedule. Thus, the combination with a reactive element seems promising to include uncertainties during project execution into the project schedule and is used in this research contribution.

Proactive-reactive (robust) scheduling approaches include anticipated uncertainty or foreseeable events into the baseline project plan and also assume a given probability distribution, e.g. in (Schatteman et al. 2008). Anticipation of future developments can be performed with reasonable scenarios and reduces the probability of revising previously made decisions (Scholl 2001 p. 139). Until now, some work has already been done in the field of proactive and reactive project scheduling for the single-mode RCPSP (Deblaere et al. 2008 p. 3). However, literature on proactive-reactive scheduling in multi-mode RCPSP (MRCPSP) is still quite rare (Deblaere et al. 2008 p. 2; Demeulemeester and Herroelen 2009 p. 164; Godinho and Branco 2012 p. 561), especially when it comes to the consideration of uncertainties without probability distributions. Proactive scheduling seems reasonable in deconstruction projects as they are often not in a quickly changing or context-sensitive environment (in those cases, reactive scheduling would be better). Robust scheduling is especially well suited in cases of considerable uncertainty and risk averseness of decision makers (Scholl 2001 p. 116). And, robust approaches allow the consideration of decision makers risk preferences.
The specific case of scenario-based robust scheduling assumes that no probability information of activity durations, cost, resource availability etc. is given. These approaches are based on discrete robust optimization (e.g. (Aissi et al. 2009 p. 428)) and are considered in recent literature for RCPSP. Here, uncertainty is modeled via scenarios that have discrete or discretized probabilities (Aissi et al. 2009 p. 428), but are rarely considered in recent literature for RCPSP yet (Artigues et al. 2013 p. 179; Mulvey et al. 1995 p. 264). As in building deconstruction, several potential scenarios of building configurations can be anticipated, that strongly influence activity durations and scheduling, a scenario-based approach

seems promising especially for considering such discrete uncertainties without probability information and is used in this research contribution.

The selection of the most appropriate project planning method depends on the modeling context, the available information and the assessing expert (Comes 2011 p. 37f.). Thus, in section 3.4, building deconstruction projects frameworks conditions and characteristics are shortly described and classified according to their most appropriate scheduling problem category. As in deconstruction projects possible building configurations or environmental conditions are known but without probabilities, decisions under severe uncertainty (see section 3.3.1) are predominant. As all possible environmental situations or scenarios (building type, size, inventory, etc.) can be anticipated but due to lacking data, at most only subjective probabilities based on (subjective) expert opinions might be used. In special cases, not even all possible environmental situations or scenarios are known ("unknown unknowns"). If severe (non-quantifiable) uncertainty is predominant (as it is in deconstruction), a possible way to deal with it is the use of scenarios (Bunn and Salo 1993; Comes 2011 p. 29), that is also used in this work.

Section 3.5 includes an overview on existing approaches in deconstruction project scheduling and planning, followed by a short excursus to construction project planning methods. Also, appropriateness of these methods in deconstruction projects and their ability to cope with uncertainties is discussed.

Project management approaches applied in the field of building and infrastructure deconstruction are limited to a relatively small number. Although (robust) RCPSP approaches and their problem variants (Artigues et al. 2013; Chtourou and Haouari 2008; Demeulemeester and Herroelen 2009; Hazir et al. 2010; Herroelen and Leus 2005) are numerous, applied works in deconstruction are rare (Schultmann 1998, 2003, Schultmann and Rentz 2001, 2003; Sunke 2009). Although there are some approaches in deconstruction project planning and management, only few approaches of Schultmann and Rentz dedicate their work to the optimization of deconstruction project planning. Mainly applied project scheduling method in deconstruction practice is CPM. In research approaches however, (M)RCPSP problem formulations dominate. As in deconstruction projects uncertainties, reworking cycles, unexpected events and resulting activities might occur and might change the schedule, the resource capacities or assignments, or the project structure, deterministic network planning techniques with single valued expectations (deterministic respective expected activity duration) are inadequate for answering the research question. Also, deterministic network planning techniques with multi-valued expectations PERT is inadequate, because it does not take resource constraints into account (Rommelfanger 1994) and thus suffers from a too limited and unrealistic problem representation. The extension of PERT by resource constraints leads to resource-constrained project scheduling problems (RCPSP) and seem to be most promising in deconstruction projects.

Scheduling applications in deconstruction projects are mainly limited to deterministic approaches yet (Schultmann 1998, 2003; Schultmann et al. 1997; Spengler 1998; Sunke 2009), that are complement the original approach of (Schultmann 1998) by several extensions. Uncertainties modeled in RCPSP in other application contexts are numerous, but applied operations research methods considering uncertainties in building and infrastructure deconstruction project planning are limited to (Schultmann 2003; Schultmann and Rentz 2003). Although fuzzy sets are an adequate tool for modeling weak data, the most advanced project management model considering uncertainties of (Schultmann 2003) faces several limitations, e.g. it does not include multi-stage planning or decision makers risk preferences. And, Schultmann and Rentz restrict to modelling the uncertain activity durations (Schultmann 2003; Schultmann and Rentz 2003) and their modelling approach does not allow an automated acquisition of building information. Instead, their calculations are based upon manual pre-measurements onsite and assessments of building documentation (if existent). Newer approaches focus on deterministic, scenario-based tactic-operative deconstruction planning based on data of a preexisting building information model (BIM) (Akbarnezhad et al. 2012, 2014; Cheng and Ma 2012). But, uncertainties and risk management approaches are not integrated. Other related approaches tackle qualitative project planning and decision making support in deconstruction (Abdullah et al. 2003; Abdullah and Anumba 2002a; b; Anumba et al. 2008) or waste quantification and deconstruction management (Akbarnezhad et al. 2012, 2014, Cheng and Ma 2011, 2012) that refrain from scheduling or uncertainty consideration.

It was shown that in deconstruction project scheduling there is only a single approach considering fuzzy activity durations. But, an uncertainty analysis, a profound consideration and integration of uncertainties into building deconstruction project planning and its impacts on deconstruction project management is lacking yet. The reviewed deconstruction project planning approaches do not consider all characteristics of deconstruction projects yet, such as (a) multi-project scheduling with multiple deconstruction sites from the contractors' perspective, or (b) multi-objective scheduling of deconstruction projects with minimum resource demand, robust schedule, maximum net present value or maximum quality level (e.g. recycling rate), or (c) locations and spatial restrictions, or (d) information updates/changes and uncertainties in the planning input information, or (e) flexible/dynamic project structure over time, or (f) risk management considering the decision makers preferences or (g) robust scheduling of deconstruction projects to generate reasonably good objective values despite changes in information, project status or resource constraints which have important practical implications.

To the authors' knowledge there is no approach that considers discrete project-specific circumstances of projects without probability information in scenarios that have influence on activity durations and resource demands. As well, there are no scenario-based (M)RCPSP approaches for deconstruction projects yet, that can handle cases where scenario probabilities are not known and provide decision makers with a subsequent robustness analysis of the generated project schedules and strategies. And, a scenario-based robust scheduling approach beyond the optimistic, expected and pessimistic cases (fuzzy sets) is not known to the author yet. To the author’s knowledge a comparable approach from general scheduling literature does not exist, yet. Furthermore, there is no approach that joins building information capture, project planning and uncertainty consideration to allow an effective way of documenting existing buildings and planning for their deconstruction, re-use and recycling.

In the following sections, a deconstruction project scheduling model formulation (chapter 4) is developed and the implementation (chapter 5) of the model is provided that closes some of the previously mentioned gaps of uncertainty consideration, information gathering, information updates and robust scheduling.

4 Development of a robust building deconstruction scheduling and decision support model under uncertainty

In chapter 4, requirements for deconstruction project planning models are formulated. Then, a model overview is given and the formal model is developed and formulated, followed by the detailed description of the single model parts A, B, C, and D. Then, the model and its classification, parameters, system boundaries and limitations, as well as its solvability are described. This is followed by a summary of the model, a critical discussion and a conclusion with further research outlook[1].

4.1 Model requirements

Modelling of real systems and decision making processes often require certain simplifications of the real situation. Assumptions on the qualitative structure of the model, on input data and on parameters as well as the implementation of model boundaries often enable modeling the process at all. These uncertainties often are subsumed under 'model uncertainty' that is hardly quantifiable (see section 3.2.5).

As depicted in section 1.2, the main challenges are to integrate numerous potential building configurations, changing information over time, robust project plans and risk preferences of decision makers into operational deconstruction planning (especially scheduling). As all projects are risky endeavors and subject to uncertainty, risk should be routinely considered from the very beginning in all aspects of the project (Munier 2014, p. 3). Deconstruction projects are projects with specific character-

[1] Parts of this chapter were previously published in (Volk et al. 2015a).

istics (see section 3.4) and are subject to uncertainty, which both has not been fully considered in recent comprehensively in recent literature (see section 3.5). The prevailing uncertainty in deconstruction projects mainly belongs to the decision characteristics of “known unknowns” with quasi ad-hoc or short-term decisions on operative level. Also, decision makers’ risk preferences are not considered in deconstruction project planning approaches yet.

The model shall be a decision support with regard to the operative project scheduling of deconstruction activities under consideration of uncertainty. In the following, the requirements for scheduling of deconstruction projects resulting from the research question and additional technical constraints are listed. In the following sections, these requirements are met and are explained in detail in the following:

I. Main objective is the minimization of project makespan. And, the model shall be able to derive deconstruction activities from a building inventory, to group the activities and to schedule the activities (groups) according to a predefined, acyclic and deterministic precedence network. The focus is on deconstruction activities and it shall be easily extendable to downstream activities such as breaking/milling, sorting, storing (containers) loading, and transporting. Furthermore, the model shall consider possible alternative deconstruction activity techniques modes with differing resource demands with regard to time, cost, resource demand and location/space. While scheduling activities, all resource and location constraints capacities/constraints shall be met over time.
II. The model shall be able to initially import and use automatically captured input data from image recognition tools that were captured during initial site inspection for building inventorying and deconstruction activity generation. This might be extendable to BIM or IFC data format for future application in retrofit projects. And, the model shall be able to proactively depict and consider foresee-

able potential building configurations and potential uncertainties in building configurations.

III. The model shall be able to assign locations to building elements and resulting deconstruction activities. It shall also consider restricted spatial conditions with respect to working areas where deconstruction activities are performed or storage space where no activities can take place. The focus is on jobsite logistics during a project; regional transportation and recycling networks are not considered.

IV. Model results shall include a baseline schedule based on a robust deconstruction strategy (= sequence of activities with assigned modes) that meets all time, location, precedence and resource restrictions. Furthermore, the robust strategy shall follow the quality robustness criterion. And, the model shall consider decision makers risk preferences and shall recommend deconstruction strategies that are adequate for the chosen risk preference. Different risk preferences can be chosen by the model user.

V. Changing information over project makespan leads to the necessary (re-)assessment of decisions. Thus, the planned model aims at a dynamic scheduling approach that shall reactively include information updates at flexible decision points (stages) during project execution, where a schedule can be updated or changed if it had become infeasible.

VI. The model shall be applicable in specific deconstruction projects of residential and similar non-residential buildings. It shall be extendable to buildings with other types of use such as all types of non-residential buildings, industrial sites, infrastructures or power plants or transferable onto similarly structured deconstruction problems of discarded transportation means or other complex products.

To meet the proposed requirements, promising methods were identified and are presented in Figure 4-1 that conclude the major model requirements and depict the selected modeling approaches to meet these requirements. In the following, this selection is further explained.

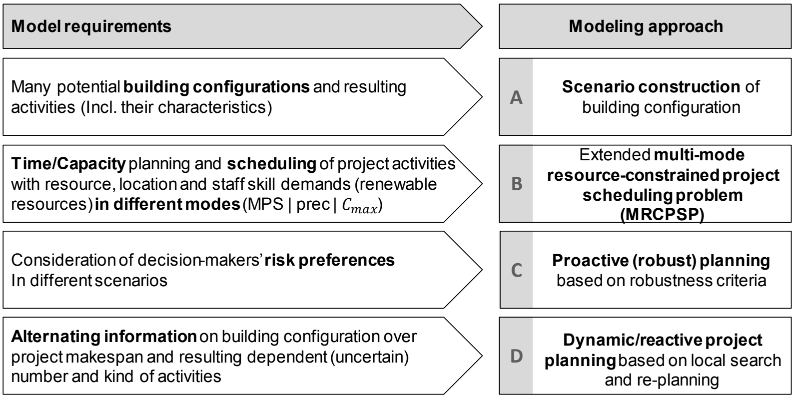

Figure 4-1: Model requirements and modelling approach

Thus, a planning and decision support model is proposed to integrate uncertainties of the planning due to the lack of comprehensive building information into deconstruction multi-mode resource-constrained project scheduling.

To meet requirement I, the following approach aims at building deconstruction optimization to find the exact solution of deconstruction project scheduling problems and thus minimizing the project makespan. Furthermore, to meet requirement II uncertain building element materials, uncertain building element masses and uncertain activity duration factors are not considered yet by literature (see Table 3-6, grey rows), but are addressed by a proactive scenario construction. Uncertainties are mostly caused by insufficient information about building inherent elements that might lead to project disturbances (e.g. activity prolongations, schedule infeasibility or rescheduling). The considered uncertainties can be described as building-related or activity-related uncertainties. Project-related or external uncertainties such as resource availabilities or weather are not in the focus here (see section 4.3.1 for further details). As probabilities of occurrence or respective distributions of building configurations (scenarios) often cannot be assumed, the solution space is discrete. As scenarios can be assumed intuitively via qualitative literature values or expertise, they are adequate to model this problem. Meeting requirements II, IV and V, the method MRCPSP is adequate due to its ability for activity and resource capacity planning under resource and precedence constraints and mode selection. As locations can be seen as renewable resources, this extension can be easily included into classical MRCPSP. To meet requirement VI, a proactive scenario-based optimization is performed, generating several feasible and optimal project schedules and allows choosing the best schedule with respect to the quality robustness criterion. Main aim is the creation of a total optimality-robust schedule to avoid multiple schedule changes. Requirement VII is met by the choice of the robustness criterion. Requirement VIII is faced by a reactive scheduling approach, which tries to find a feasible schedule, after the baseline schedule had become infeasible (e.g. due to an unexpected event). If the baseline strategy becomes infeasible during project execution, a reactive scheduling leads to the selection of a 'near' deconstruction strategy. Requirements IX and X are met by a modular model structure with import functionalities from MS Excel and graphical user interfaces, that is able to inventory building elements' spatial measures and masses from a CSV input data file.

In the following subsections, the development of the formal model is described in detail. Therefore, first a model overview is given. Then, the four main model parts (A), (B), (C) and (D) are described. Then, a problem classification is given, followed by a short discussion of problem size, problem solvability and potential solver qualities.

4.2 Model overview

To find a robust deconstruction schedule taking into account uncertainties, a MRCPSP approach is formulated and solved (B) for several potential scenarios of building configurations (A). Based on the result of the solved MRCPSP, optimal deconstruction strategies[2] (C) and recommendations for decision making in deconstruction projects are given. In the case of schedule infeasibility during project execution, a reactive approach (D) is proposed to regain a feasible schedule by local search or rescheduling. The model functionalities and their relations are graphically shown in Figure 4-2.

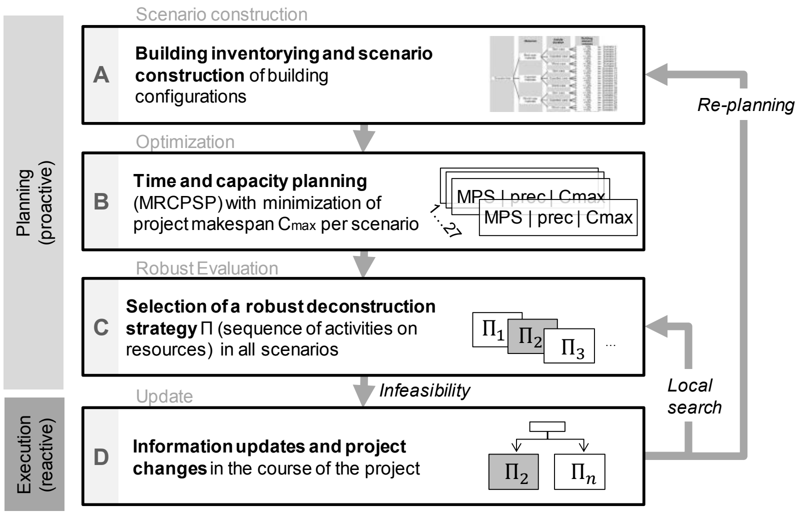

Figure 4-2: Model functionalities with information updates at every stage s

Aiming at increased planning reliability and inclusion of risks and uncertainties in deconstruction projects, the approach integrates the two

[2] In scheduling literature, these are also called scheduling policies.

concepts of 'scenario generation' and of robust 'job shop scheduling' or 'RCPSP' optimization. Main aim of this approach is the implementation of a proactive-reactive project scheduling approach for building deconstruction that is proactively considering potential scenarios at project start and reactively responding to project disruptions during project execution. This results in a robust (dominating) scheduling strategy for all assumed scenarios, combined with a reactive scheduling approach in the case of strategy infeasibility.

Due to the buildings' uniqueness, the assignment of probabilities of occurrences (e.g. of activity durations or building element existence) is difficult and often impossible. Often, the exact configuration of a building and consequently the number of deconstruction activities and their characteristics are not exactly known before deconstruction project start. Thus to integrate building configuration uncertainty into the decision process, a scenario construction (A) consisting in an automated generation of building configurations at stage $s = 0$ before project start is applied[3]. This scenario generation is based on information from an initial observation $\xi_{s=0}$ (site inspection or documentation review) at stage $s = 0$. Also, the scenario construction includes expert estimates on optimistic, expected and pessimistic activity durations. The creation of potential scenarios for potential building configurations and related deconstruction activity durations is a possibility to handle the occurring foreseeable uncertainties[4]. From these potential scenarios, deconstruction activities and activity durations can be derived and scheduled. A stochastic approach is theoretically possible, but assumptions on the most appropriate activity duration distribution and its parameters can

[3] Stages s (decision or information update points) are different from time periods t (Birge and Louveaux 2011 p. 59; Scholl 2001 p. 35). See also section 3.2.5 for definitions.

[4] See also section 2.3.1 regarding building auditing and section 4.3 for a detailed description of the model input data (CSV/OBJ interface) and the scenario construction.

only be estimated[5]. Therefore, scenarios and expert estimates (similar to fuzzy sets) are used as described above to realistically represent the projects' scheduling problems. More information is provided in section 4.3. For each scenario z_k, a MRCPSP is solved minimizing the project makespan (B) with resulting optimal objective values and schedules to plan deconstruction activities on an operational level. Model result is an optimal, feasible schedule (or rather strategy) for each scenario $z_{k,s}$ in stage s including all available information for project planning at this time. As time is discretely modeled, the scheduling model is a discrete optimization model with scenario-based activity durations. Furthermore, activity-on-node network is applied to describe activities' precedence relations. The activities' precedence represented in an acyclic activity-on-node network represents the technically mandatory order in deconstruction projects (see also Figure 2-8). This deconstruction precedence is comparable to a reversal of construction precedence (Schultmann 1998) implying that in both cases similar project management methods are applicable. Activity-on-node modeling is used, because in deconstruction projects activities are omnipresent, rather than events that can be interpreted as disruptive elements in the project schedule. As all nodes of the network need to be visited and respectively all activities have to be scheduled, CPM, MPM or PERT methods are applicable. As deconstruction projects often are performed under time, cost and resource constraints, this problem form is applicable to answer the actual research question. In deconstruction projects, main objective is the minimization of project makespan (Schultmann 1998). Although there are approaches of cost minimization (e.g. in nuclear power plants), this approach as well as main research approaches and deconstruction

[5] Some literature source name the beta distribution as useful for activity duration modeling in general and also in construction projects (Chen and Li 2006; Nickel et al. 2014 p. 166), because it has upper and lower bounds and right-skewness. Before their potential implementation in deconstruction scheduling, the adequacy of the beta distribution for deconstruction activity durations has to be proven e.g. by experts or experience databases or finished projects' documentations.

projects in practice follow the minimization of project makespan principle. For more information see section 3.4.

The resulting project strategies are then applied to all scenarios and an evaluation and comparison of alternative strategies (C) is performed. Thus is done by means of the optimum machine assignments and their sequence of the schedules as well as by objective values, to identify robust alternatives at stage s. The evaluation of different strategies allows model users and decision makers to identify strategies that perform well over several or all scenarios. Furthermore, this enables decision makers to transparently include their risk preference into decision making. Different robustness criteria are applied according to the decision makers' risk preferences resulting in differing robust solutions. For more information see section 4.5.

Project scheduling under uncertainty is a multistage problem, "where decisions are made, when new information becomes available" (Kall and Wallace 2003 p. 304)[6]. Due to these timely interdependences, a static environment often cannot be assumed under uncertain conditions (Scholl 2001 p. 32). Thus, a new (building- or project-related) information update (D) at stage $s+1$ is assumed, when the project execution leads to schedule or strategy infeasibility. If this is the case, a local search is performed in the already identified and evaluated deconstruction strategies. If a "near" and feasible strategy is found, the baseline strategy is changed to the newly identified strategy and the resulting schedule and resource demand is calculated. Otherwise, if there is no "near" feasible strategy, the model can be re-used with the remaining activities that have not been performed yet. The re-use includes the creation of a new optimal baseline schedule based on the new information status at stage s on building configuration for the remaining building elements. The information updates can arise from further site inspections, measurements and status reporting. With the project state in s and the information update in mind, a subsequent schedule can be calculated for the

[6] See (Kall and Wallace 2003 p. 304) for the discussion on two-stage scheduling problems.

remaining activities and their assumed durations for $s + 1$. When all scenarios are scheduled, the results can be evaluated and a best strategy over the whole makespan and all scenarios can be identified via ranking. For more information see section 4.6.

Expected results of the model are a robust activity sequence on resources (deconstruction strategy) and a reactive component that supports decision makers in the case of strategy infeasibility during project execution. This model has the following characteristics: it is a partly open model, allowing data input and parameter adjustments. Moreover, the model has a dynamic component (part D) and allows rescheduling after inserting the current project state and the changed project conditions. The model is deterministic as there are no probabilities of occurrence known, but on a scenario basis uncertainties are considered. As the time or project duration is modeled and optimized, the model restricts to discrete, binary decision variables. The applied methods in the parts can be differentiated into a simulation part (part A), optimization part (part B), an evaluation part (part C) and a reactive part (part D). The application of the model follows the purpose of a decision making planning model for decision maker in deconstruction projects.

As scenarios are considered with point-estimated values, the developed model falls into the category of expected-value approaches that does the project planning for all scenarios as it substitutes uncertain values with several deterministic values (here: minimum, expected and maximum activity duration) depending on the scenario. And, it is combined with a wait-and-see approach regarding uncertainties occurring during project execution. The use of scenarios allows the integration of expert knowledge and experience values. Since uncertainty is mostly caused by building inherent elements, in a first step this approach restricts to the proactive creation of a robust schedule avoiding multiple changes in schedules (expected-value). Other uncertainties onsite during project execution such as resource availability can be considered in a second step e.g. via reactive scheduling (part D) or repairing methods in multi-period scheduling (wait-and-see).

The comparison of the problem setting with general approaches in OR literature, project management, risk management and research approaches in deconstruction scheduling and capacity planning as well as the discussion on their suitability, applicability or transferability onto the problem context can be found in sections 3.4, 3.5 and 3.7. In the following sections, the single steps of scenario construction (section 4.3), scheduling and optimization (section 4.3.1), selection of promising alternatives (4.5), and information updates (section 4.6) are detailed.

4.3 Model part A: Building inventorying and scenario construction[7]

Figure 4-3 shows the main steps of calculation in model part A. A CSV/OBJ interface lists all detected and visible building elements with their coordinates and material information. Based on this list of building elements, further invisible building elements are derived. E.g. if the list presents a wall, in a first step wall values (such as length, height) are checked on plausibility. However, if the building element information has no characteristic value between a lower and an upper bound that can be found in standards, it is adjusted to plausible values within these boundaries.

When it comes to technical building equipment, wiring, piping and tubes often are not visible to the eyes or to sensors. However, often their outlets such as switches, lamps, outlets, sanitary devices, etc. are visible and allow a reconstruction of their conduits depending on the type of technical equipment and the position of the technical outlet as well as on the position of the next technical distribution point. Similar to the wiring reconstruction, pipes and tubes are reconstructed and their volume and mass is calculated.

The here applied scenario construction contains several constructing, inventorying and grouping steps. Before starting the scenario construc-

[7] Parts of this section have been published previously in (Volk et al. 2015a; b).

tion, a reasoning of occurring uncertainties (section 4.3.1) and an initial building assessment is performed (see section 4.3.2) and then followed by an initial scenario construction (see section 4.3.6). This scenario construction method has to be applied since the quantification of probabilities of occurrences of building configurations is not possible. In the scenario construction only foreseeable uncertainties are considered, the unpredictable and unknown uncertainties and schedule disruptions are not considered. Then, project activities are derived per scenario from the building inventories and grouped to activity sets (see section 4.4.1) and are scheduled in model part B (see section 4.4). In the following sections, a detailed description of model part A is given.

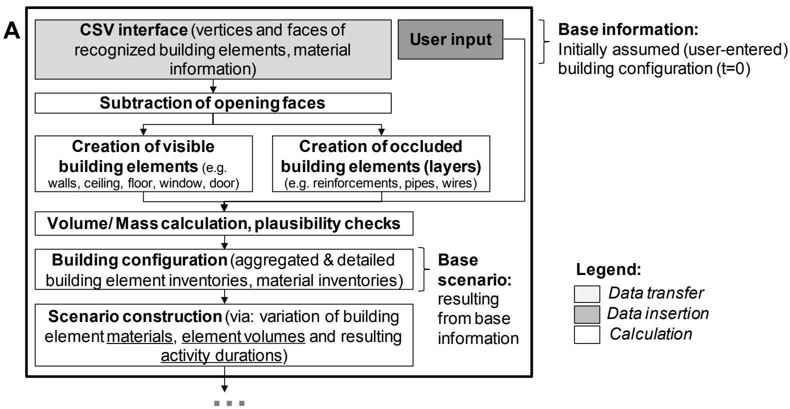

Figure 4-3: Overview on model part A

4.3.1 Uncertainties in deconstruction projects (planning and execution)

The consideration of uncertainties in the planning phase of deconstruction projects is crucial to reduce disruptions, schedule infeasibility and project vulnerability during project execution. In this section, the occurrence of uncertainties in deconstruction projects is addressed and main uncertainties in deconstruction projects are identified. In deconstruction projects, main sources of uncertainties are the exact building configuration (set of building elements and their specific properties) which has major impact on the existence or the non-existence of activities, real processing times of activities, onsite resources such as location availability and resource capacity of staff, hydraulic excavators, site equipment or containers as well as neighborhood conditions.

There are several reasons for occurring uncertainties in buildings and structures. Buildings can be classified according to several characteristics, but due to their type of construction, their use and their long lifetime buildings are unique, complex products. And, due to long life cycles of buildings and their building elements, information loss occurs during building use over decades. Moreover, retrofits, extensions of buildings, building wings or elements etc. often are not well structured and comprehensively documented. Also, due to different construction traditions and changing availability of building materials there are regional and specific differences that might not be depicted by building documentation or building typologies. To the authors' knowledge, these uncertainties (without probabilities of occurrences) have yet not been classified and systematically integrated in deconstruction project planning literature and especially not in resource-constrained multi-mode scheduling.

Occurring uncertainties in projects can be differentiated into external and internal uncertainties (Li et al. 2006). Both types may lead to prolongation of activities and of the whole project makespan. Project-related (external) uncertainties for planning and execution (see Figure 4-4, white boxes) mainly consist in resource availability and other external uncertainty. In contrast to that, building element-related (internal) uncertainties for planning and execution include the characteristics of building elements such as the material or mass of the elements (see Figure 4-4, dark grey boxes). Activity-related (internal) uncertainties for planning and execution (see Figure 4-4, light grey boxes) are the activity durations, the potentially changing resource demand or disruptions. Activity-related uncertainties can also contain epistemic uncertainties which can for example be represented by a minimum, expected and maximum duration per activity. Figure 4-4 shows the here considered internal (dark grey) and external (white) uncertainties and their influences on activity-related uncertainties. E.g. the uncertain building element volume (3) has an influence on the activity resource demand (9), but not on additional or omitting activities (8).

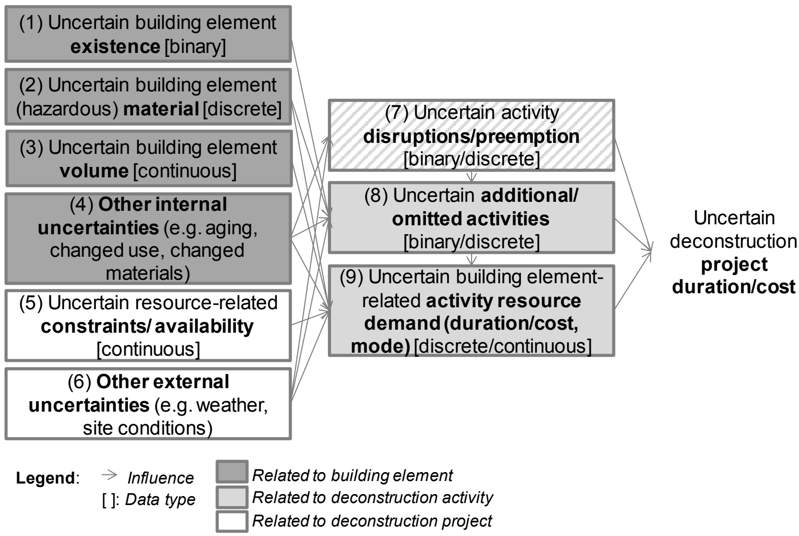

Figure 4-4: Occurring types of internal (light and dark grey) and external (white) uncertainties and their influences in planning of building deconstruction projects[8]

Internal uncertainties are part of the production system (production system risks) and thus in the responsibility of the deconstructor (Kenley and Seppänen 2010 p. 181ff). Here, internal uncertainties are defined as building element and activity related uncertainty, while external uncer-

[8] Potential types of uncertainties in construction projects are listed in literature e.g. in (Kenley and Seppänen 2010 p. 181ff; Schatteman et al. 2008 p. 5) and are partly similar to those occurring in deconstruction projects regarding: weather, prerequisites, adding resources, productivity rates (skills), quantities, resource availability, locations or quality.

tainties subsume other uncertainty e.g. resulting from weather, corporate activities etc.[9] Internal uncertainties (dark grey) on building element level can be differentiated into (1) existence of building elements, (2) building element property realization with respect to material (incl. hazardous materials, density/concentration, coverings/coatings/insulation) (3) spatial dimensions of building elements (x, y, z, volume) and other (4) internal uncertainties. As building element-related uncertainties (1)-(3) are theoretically measurable onsite, they belong to epistemic uncertainties. This means, that with increased inspection and measurement efforts, these uncertainties could theoretically be reduced. Internal uncertainties (4) such as aging, changed use (e.g. modifications) or changed materials (e.g. corrosion) are also theoretically measurable and thus epistemic. But this information is often not measurable in practice and related with an even higher effort and requirement of technical equipment and staff.

External uncertainties on project level include (5) resource constraints or availability e.g. due dates, ready times or deadlines or available machines and (6) other external uncertainties like weather, site or legal conditions. External uncertainties such as weather are not the deconstruction operators' or the contractors' responsibility (Kenley and Seppänen 2010 p. 181ff) and thus are neglected in the further decision modeling. Uncertainties (5) and (6) are considered as external and thus are aleatoric uncertainties with an assumed/known probability of occurrence.

On deconstruction activity level, uncertain activity disruptions (7) might occur due to unexpected findings onsite and necessary sampling/testing which equals uncertainty (2), omitted or additional deconstruction activities (8) including deconstruction activities' precedence/project structure might arise, or resource demands (9) of deconstruction activities might change (durations, activity mode, personal, machines, equip-

[9] See section 3.2.1 for a definition and comprehensive overview on uncertainty.

ment) and result in changed deconstruction costs, recycling (sorting, reprocessing) costs/revenues, disposal and transportation costs. Uncertainty (7) with activity disruptions belong to aleatoric uncertainty, because process/activity disruptions e.g. caused by staff illness, unexpected findings in a building etc. cannot be anticipated in time or length and occur by chance. Uncertainty (8) with additional or omitting activities is depending on uncertainties (1) and (2) and thus can also be classified as epistemic uncertainty. Similar as the previous uncertainty, uncertain resource demand of activities (9) depends on uncertainties (2) and (3) and thus can also be classified as epistemic uncertainty.
As consideration of all uncertainties is impossible, the developed model restricts to the most relevant uncertainties (1), (2), (3) and (5) in deconstruction planning and their resulting uncertainties (7)-(9). This will be subject of the following subsections.

4.3.2 Initial building assessment and creation of building inventories

Figure 4-5 shows the general approach in the developed building element inventory and material inventory creation, which calculates building element surfaces, volumes and masses that are then used as an initial observation data input to model part A for the following scenario construction (see section 4.3.2). The inventorying uses three main data sources: a CSV/OBJ interface, user input and database information. The CSV/OBJ interface information is based on geometric and categorical building element information such as provided by a software tool ResourceApp developed by Fraunhofer IGD (see Table 5-2 for an exemplary dataset). The interface contains the building elements itself, their material, their coordinates and their spatial relationship (e.g. an outlet of technical equipment has information attached regarding its reference wall). The user input includes general building information and building parameters such as the building name, the address, the construction type or the building ports of the technical equipment's. Figure 5-4 and

Figure 5-5 show the respective graphical user interfaces. The imported database information consists of building element characteristics such as material information, material densities, building element thicknesses, parameters for reinforcement calculation or for material fractions inherent in specific building elements that are used for building inventory calculation. These values follow technical standards and literature. Also, the parameters can easily be imported via MS Excel interface and model users are able to modify the parameters in MS Excel or in the respective graphical user interface easily (see section 5.1.1 and Figure 5-5 for details).

The initial observation at the building site is the base for a building assessment, a potential consideration of uncertainties e.g. by scenarios and deconstruction project planning. Software tools such as the ResourceApp developed by Fraunhofer IGD[10] allows the automated recognition of building elements in rooms via the captured color and depth information. If not automatically recognized, the user can assure the identity of building elements and can append the building element property 'material information'. For this purpose, a Microsoft Kinect sensor in conjunction with a high-performance laptop, a data preprocessing and recognition algorithms is used. The Microsoft Kinect sensor combines a RGB camera with 3D depth sensor with a structured light approach and was primarily developed for the recognition of human gestures. The developed software tool of Fraunhofer IGD processes the sensor information to detect building elements in the captured point cloud data (image and depth information). The identified building elements and related information of spatial coordinates captured by the sensor and the material information inserted by the user can be exported via CSV and OBJ interface.

[10] This tool was developed by Fraunhofer IGD during the BMBF-funded project ResourceApp. Details on the software tool can be found in in (Volk et al. 2015b) or in the respective project documentation.

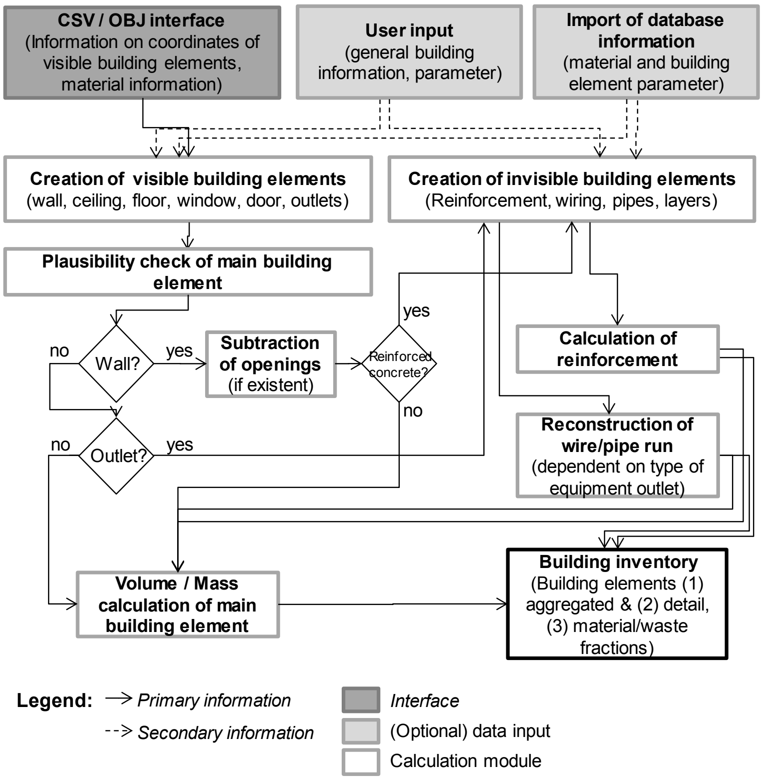

Figure 4-5: General overview on building element inventory functionality

The CSV/OBJ input data differentiates facial and vertex building elements e. Facial building elements are elements with a considerable surface that can be detected during site inspection such as walls, ceilings, floors, windows or doors. Vertex building elements include elements that can be characterized by a vertex port appearance, such as electrical outlets and switches, freshwater taps, sinks, shower basins, etc. To create the building element inventory, the volume and masses of these main building element groups are calculated in different ways.

Furthermore, visible and non-visible building element can be differentiated. Visible building elements are e.g. floor covering, wall covering, electrical outlets or sanitary equipment. Non-visible building elements exist in the building but cannot be detected by the sensor or be seen, e.g. wiring or piping in a wall, the wall construction (bricks or reinforced concrete) or the floor reinforcement. In the case of non-visible elements, elements and their properties are assumed and calculated via semantic information from experts and standards. The following subsection describes the inventory calculation process in detail.

4.3.3 Calculation of facial building elements

From imported CSV/OBJ interface information, the facial building elements' surface $A_{e\prime,f}$ is calculated by the cross product of two linear independent vectors $\overrightarrow{v_1}, \overrightarrow{v_2} \in V_{e\prime,l}$ that are lying on the facial building element under consideration by $A_{e\prime,f} = \overrightarrow{v_1} \times \overrightarrow{v_2}$. $V_{e\prime,f}$ represents the set of all vectors $\vec{v}$ that can be calculated from the facial building elements' e corner coordinates via vector subtraction. The facial building element volume $V_{e\prime,f}$ is calculated by $V_{e\prime,f} = A_{e\prime,f} * \delta_{e\prime}$ with the thickness information $\delta_{e\prime}$ assumed by their typical physical dimensions that can be found in national technical standards per building element (e.g. a wall has standardized thicknesses such as 17.5 cm, 24 cm or 36 cm, see DIN 4172:1955-07).

If openings have been detected, the respective opening surface is subtracted from the reference wall (e') before the reference building elements' surface, volume and mass is calculated as formally also described by (Seemann 2003 p. 109) as:

$$\boldsymbol{A_{e\prime}} = \boldsymbol{A'_{e\prime}} - \sum_{\tilde{e} \in \widetilde{E} \mid \tilde{e}_{e'}} \boldsymbol{A_{\tilde{e}}} \tag{4.1}$$

with $A'_{e\prime}$ as building element face of the reference building element (wall) determined by the outer dimensions, and set E of building elements openings $\tilde{e}$ that are enclosed by building element e' (wall) ($\tilde{e}_{e\prime}$). As each room is recorded individually from an indoor perspective and afterwards the rooms are put together in a 3D model, identical building elements are recorded from both sides. Especially interior building elements of walls, ceilings and floors that are audited from both sides, are listed twice in the building element data set. Interior and exterior building elements are automatically identified to calculate the correct building element volume and to avoid double counts. Identification of parallel elements (interior elements) is done via normal vectors orthogonal to the element surfaces (parallel elements = normal vectors of two building elements are linear dependent). Then, the distances between the all element surfaces are determined via Hesse normal form $H\colon \overrightarrow{v_1} * \overrightarrow{v_2} = \Delta$ and the difference $\Delta(H_1, H_2) = \frac{|\Delta_1 - \Delta_2|}{|\overrightarrow{v_1}|}$ between respective planes (via their supporting vectors)[11]. If the difference between surfaces is below a defined level (default value: 0.5m for walls, ceilings and floors) then it is assumed that both surfaces belong to the same building element. Then, to avoid double counts of interior walls, ceilings and floors, the half element thickness $\delta_{e'}$ is taken for volume and mass calculation:

$$\boldsymbol{V_{e',f}} = \boldsymbol{A_{e',f}} * \boldsymbol{\delta_{e'}}/\mathbf{2} \tag{4.2}$$

and

$$\boldsymbol{M_{e',f}} = \boldsymbol{V_{e',f}} * \boldsymbol{\rho_{e',y}}. \tag{4.3}$$

However, load-bearing and non-load-bearing walls cannot be differentiated yet.

As all building elements are captured from an indoor perspective, this induces an error of unconsidered room corners for interior walls (see

[11] See (Merziger and Wirth 2002 p. 147ff.) for further information on Hesse’sche normal form.

Figure 4-6, right part) which occur in interior wall calculation. Thus, in the calculation of each interior wall a correcting term of

$$\boldsymbol{\varepsilon} = \boldsymbol{\delta}_{e'}^{2} * \boldsymbol{h}_{e'} \tag{4.4}$$

per interior wall per room with building element height $h_{e'}$ is inserted to reduce the error. However, in rooms with one or more exterior walls, this will induce an error of

$$\boldsymbol{error} = (\boldsymbol{\delta}_{e'}/\mathbf{2})^{\mathbf{2}} * \boldsymbol{h}_{e'} * (\boldsymbol{numberOfExterior\ Walls}) \tag{4.5}$$

per room. Interior ceilings and floors are similarly calculated with half building element height $h_{e'}$. The same consideration also applies for interior doors and windows. The reference wall of the respective opening is identified and it is checked if it is an external or an internal wall. Depending on the walls' property, the doors' or windows' volume and mass is either calculated with its half thickness (interior building element) or with its full thickness (exterior element).
External building elements that belong to the building envelope are also identified and their volume is calculated separately. Exterior facial building elements are defined as elements without a parallel building element surface, e.g. exterior walls, windows or doors. However, external building elements like façade elements cannot be detected by the applied indoor sensor and are not calculated yet. Volumes of exterior walls, upper ceilings and lower floors are calculated by the multiplication of their visible surface times their known or assumed thickness (which cannot yet be acquired automatically) by

$$\boldsymbol{V}_{\boldsymbol{e',f}} = \boldsymbol{A}_{\boldsymbol{e',f}} * \boldsymbol{\delta}_{e'}. \tag{4.6}$$

As the outside of a building is not assessed by the Fraunhofer IGD sensor and thus respective buildings elements are not listed, the building element volume is calculated with the full building element thickness $\delta_{e'}$.

Also, non-visible parts of exterior walls are considered in volume calculation to reduce inventory error. For walls, the correcting term for non-visible wall corners (see Figure 4-6, left part) is

$$\boldsymbol{\varepsilon}_{\boldsymbol{wall,=}} = \boldsymbol{\delta}_{\boldsymbol{e'}}^{\boldsymbol{2}} * \boldsymbol{h}_{\boldsymbol{e'}} \tag{4.7}$$

per wall. As a differentiation of exterior or interior walls is not made in the correcting factor, an error occurs if the wall thicknesses of adjacent walls are differing. The error can be quantified as

$$\boldsymbol{\varepsilon}_{\boldsymbol{wall,\Delta}} = \boldsymbol{\delta}_{\boldsymbol{e'1}} * (|\boldsymbol{\delta}_{\boldsymbol{e'1}} - \boldsymbol{\delta}_{\boldsymbol{e'2}}|) * \boldsymbol{h}_{\boldsymbol{e'}} \tag{4.8}$$

per room corner with different wall thicknesses. E.g. in the case of 0.245 m and 0.365 m walls of a height of 2.50m, the error is

$$\boldsymbol{\delta}_{\boldsymbol{e'1}} * (|\boldsymbol{\delta}_{\boldsymbol{e'1}} - \boldsymbol{\delta}_{\boldsymbol{e'2}}|) * \boldsymbol{h}_{\boldsymbol{e'}} = 0.0438 \text{ m} * 2.50 \text{ m} = 0.1095 \text{ m}^3. \tag{4.9}$$

This error can be further reduced by the determination of neighboring walls thicknesses and the correct calculation of the correcting factor ε. However, here this error is accepted as it seems considerably low compared to the walls total volume and as it only occurs in the case if adjacent walls have differing thicknesses.

Figure 4-6 and Figure 4-7 show the volume calculation of exterior and interior walls graphically. In Figure 4-6, the 'missing' or 'invisible' corners of exterior and interior walls can be seen in a schematic floor plan. Also the correction factor ε_{wall} can be seen which is included into the volume calculation. Figure 4-7 shows the connection of walls with differing thicknesses and the related error (black triangles), which is considered as epistemic model uncertainty. This error could be reduced by further modelling effort, identifying the neighboring walls thicknesses. However, as the error seems comparably small to the walls total volume, this error is neglected in this research contribution but future developments of the model could reduce this error.

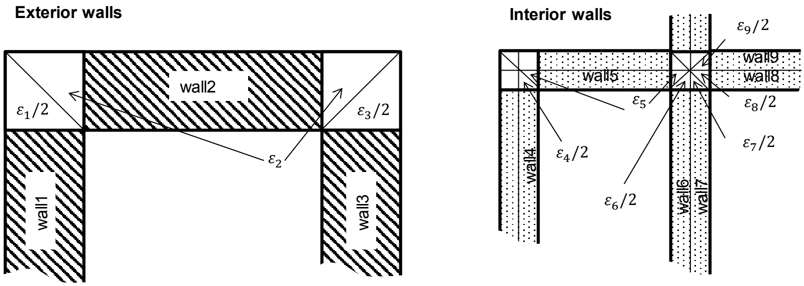

Figure 4-6: Schematic cutaway floor plan of exterior and interior walls and correction factor ε in exterior (left) and in interior (right) wall volume calculation

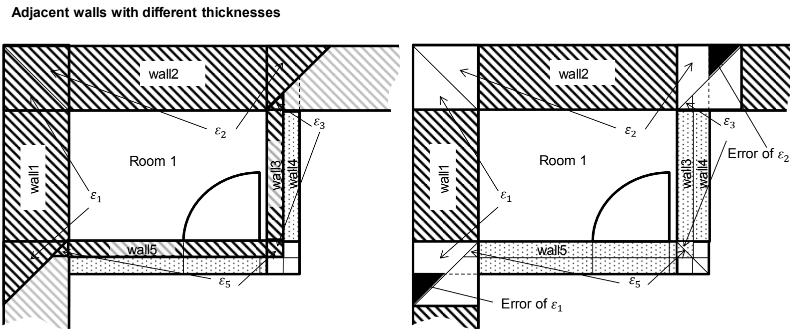

Figure 4-7: Schematic cutaway floor plan of exterior and interior walls in volume calculation (black hatched parts in left sketch) and wall error in the case of adjacent wall with differing thicknesses (black triangles in right sketch)

Upper ceilings and lower floors are also identified and calculated with their total building element height h_e. Also, their volume lying on the surrounding room walls is included by the half of the walls' thicknesses, so that 'invisible' floor and ceiling corners are corrected by

$$\boldsymbol{\varepsilon_{ceil./floor}} = \boldsymbol{l_{ceil./floor}} * \boldsymbol{w_{ceil./floor}} * \boldsymbol{\delta_{wall}} \,. \tag{4.10}$$

Then, the building element volume is calculated via multiplication of the visible surface extended by the half wall overlap correction factor $\varepsilon_{ceil./floor}$ and multiplied by the total height $h_{e\prime}$. A special case is the calculation of 'invisible' foundation surfaces, volumes and masses. The model is able to calculate three types of foundations: single foundations and stripe foundations (e.g. beneath garages and small construction) and foundation plates (under buildings). All types of considered foundations as lower enveloping building elements have a wall overlap (1x wall thickness δ_{wall}) and a protrusion of the foundations beyond the walls (2x wall thickness δ_{wall}) is also considered per wall type and multiplied with the height

$$\boldsymbol{h_{e\prime}} = \boldsymbol{h_{foundation}} - \boldsymbol{h_{floor}}. \tag{4.11}$$

As the walls are not differentiated into interior or exterior walls in foundation volume calculation yet, just 1.5x wall thickness is added to the visible foundation plate surface length and width in this calculation. The further detailing of the calculation might also be subject to future research. In the case of individual foundation or strip foundation beneath the walls the respective volume and mass of these additional, invisible building elements is calculated. The described error in ceiling and floor volume calculation can further be reduced via integration of room-wise information on inherent wall types (interior, exterior) and their adjacencies. However, in further inventory calculation, this error is negligible compared to the total walls', ceilings' and floors' volumes of several rooms or even residential houses.

If the facial building element consists of a 'single' or 'homogeneous' material (e.g. brick, concrete, timber), the building element mass M_e is calculated via multiplication of element volume V_e, and material density $\rho_{e\prime,y}$ of respective materials y by formula (4.3). However, if the material information reveals that there are multiple layers of material on the building element (e.g. the material information of 'gypsum' or 'plaster'), these layers are treated as individual building elements and inserted in a detailed building element inventory that also includes non-visible building elements. Otherwise, if the facial building element is made of reinforced concrete, the reinforcement is calculated via standard reinforcement coefficients per square meter of ceiling, wall or floor surface[12]. Then, the reinforcement volume is subtracted from the total building element volume. For both reinforcement material and matrix material, masses are calculated with their densities and listed in the detailed building inventory. Here, a further detailed calculation of the reinforcements according to construction standards and building static standards was implemented for a modular garage testing object, but for whole buildings the reinforcement calculations are very complex and might be subject of future research and model extension.

Other invisible facial building elements are calculated with inventorying parameters. Default values of the parameters are proposed by the model and can be modified in a graphical user interface (see Figure 5-5). E.g. to simplify the building inventorying of non-contaminated building elements, literature proposes the thickness of stripe foundations under terrain of 1 m, thickness of foundation plates of 0.2 m, as well as the weight of steel or timber roof construction beams with respect to the buildings ground floor area (see Table 2.1, Abb. 2.6, Table 2.2, Table 2.3 in (Lippok and Korth 2007 p. 117ff.)). Also, specific regulations of the calculation of inclined surfaces have to be kept, e.g. in the inventorying of roofs the mass of building elements increases by 10 % at 25° degree, 20 % at 35° degree, 30 % at 40° degree, 40 % at 45° degree and 100 % at 60° degree inclination (Lippok and Korth 2007 p. 117ff.). And, protrusions and overlaps have also to be considered in inventorying (Lippok and Korth 2007 p. 117ff.). In the current model, the roof inventorying was not implemented, but in future model extensions the regulations for roof inventorying have to be applied.

[12] Mainly applied reinforcement calculation in reinforced concrete is based on kg/m² (Lippok and Korth 2007 p. 354).

The calculation of the building inventory follows the reference inventorying and accounting units per building element and per material by TV Abbrucharbeiten (see also Table 2-6) especially for floor coverings, wall coverings and ceiling coverings, plaster, tiling, screed, insulation and separation/partition walls. Roof coverings and roof constructions, as well as building element cutting is not considered in this model but can easily be included in further model extensions.

4.3.4 Calculation of vertex building elements

From imported information via CSV-interface, the vertex building elements' surface, volume and mass is assumed via technical standards for each building element type (e.g. an electrical outlet or switch has a standardized size of ca. 49 cm²). Based on the type of vertex building element, the associated occluded pipe or wire is reconstructed backwards from the outlets to the previous distribution units to the building port[13] of the respective building equipment. This is done by information of technical standards about the running of different technical equipment (e.g. DIN 18015 for electrical wiring).

For example, if electrical equipment (lamp, outlet, switch) was detected in a room, its wiring is reconstructed to the 'next' distribution box. Distribution boxes are hierarchically modelled for rooms, stories and buildings. In this case, the 'next' distribution box is a room distribution point. In the first step, the wiring is reconstructed from the outlet to a distribution point in the same room that is assumed next to the door. From this 'invisible' distribution box, its backward wiring again is calculated from the room in question to the distribution box of the building story. Then, from the story distribution box the wiring is reconstructed to the respective building port with the main power connection point of the building. The wiring reconstruction logic follows the Manhattan distance

[13] Information regarding building distribution ports' and storey distribution boxes coordinates are pre-requisite for the following calculations.

metric[14], but with the restriction that only three horizontal zones (upper, center, lower) are possible and windows and doors have to be bypassed on the upper zone. The upper zone is located 0.30 m below the ceiling, the center zone is located 1.15 m above the floor and the lower zone is calculated 0.30 m above the floor (see Figure 4-8 above and bottom left). Furthermore, openings (windows, doors) have to be bypassed with a distance of 0.30 m. Vertical wiring is only allowed with 0.30 m distance next to openings and room corners. These restrictions follow the German standard for wiring positioning in DIN 18015-03:2007-09. However, the wiring conduit of Figure 4-8 bottom right on floors (below the floor covering) or below the ceilings (between ceiling construction and a suspended ceiling) is not considered here and might be subject to model extensions. The mentioned distribution boxes have an assumed standard mass and volume and are listed as 'invisible' building elements in the detailed building inventory. Also, the reconstructed wiring is listed in the detailed building inventory as 'invisible' building elements. However, their volume and mass is calculated based on the reconstruction. To calculate the wiring volume $V_{e'}$, the wiring length $l_{e'}$ is multiplied with an assumed wiring diameter δ_e based on standards in residential buildings: $V_{e'} = l_{e'} * \delta_{e'}$. To compute the mass of the wiring element, a 30% percentage of the volume is assumed to be the conductors' volume (copper), according to experience values from practitioners and established scrap metal trading standards. The insulation matrix material is assumed to be polyvinyl chloride (PVC). The calculated building element masses of invisible wiring and piping is also inserted in a detailed building element inventory. The piping of water and heat equipment is similarly reconstructed. The number of standard regarding the installation of drinking and waste water installations is vast (e.g. for piping installation: DIN 806-2, DIN 806-3, DIN 806-4, DIN 1986, DIN 1988; piping materials and their spatial dimensions: DIN 2460, DIN 806-3, DIN 8077 to DIN 8080,

[14] The Manhattan distance metric calculated the distance in the three dimensional spacebetween the points A and B as follows: $\Delta(A,B) = \sum_{i=1}^{3}|A_i - B_i|$.

EN ISO 15874 to EN ISO 15877 all parts, DIN EN 1057, DIN EN 13349, DIN EN 14628, DIN EN 15542, DIN EN ISO 6708; sanitary equipment, armature and valves: DIN 19635-100, DIN EN 200, DIN EN 816, DIN EN 817, DIN EN 1111, DIN EN 1112, DIN EN 13828, DVGW W 574, DIN 4109).

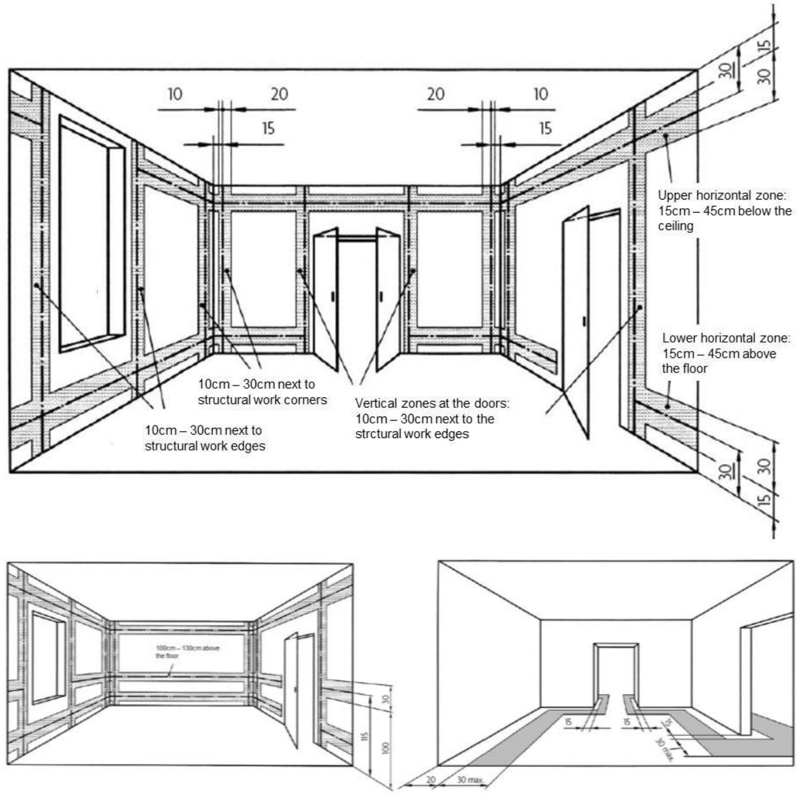

Figure 4-8: Vertical and horizontal wiring conduit zones in residential buildings[15]

[15] According to DIN 18015-03:2007-09.

However, due to a lacking standard on the exact positions of room or story distribution points' locations and the conduit of the piping the reconstruction follows slightly different rules. For sanitary equipment, the cold and hot drinking water piping is calculated, as well as the waste water piping. For (hot) drinking water, the pipe has to be installed in the shortest possible way by standard (see DIN 1988-100:2011-08, DIN 1988-200:2012-05) to ensure that the pipe water volume between boiler and outlet is less than 3 liters (DIN 1988-200:2012-05). Otherwise, if the upper limit of 3 liters in the pipe between the farthest outlet and the boiler cannot be kept, a circulation system has to be installed (DIN 1988-200:2012-05). Furthermore, the conduit has to be straight, parallel and without crossings (DIN 1988-200:2012-05). Thus, for all types of pipes, the minimum Manhattan distance metric is applied to the three spatial dimensions to calculate the pipe length.
Then, the piping length l_e [m] is multiplied with an assumed pipe diameter ($d_{in,e'}$ [mm]: inner pipe diameter, $d_{out,e'}$ [mm]: outer pipe diameter) and pipe wall thickness $\delta_{e'}$ [mm] (according to DIN 1057:2010-06):

$$\begin{aligned} \boldsymbol{V_{piping}} &= \boldsymbol{l_{e'} * d_{in,e'} * \delta_{e'} * \pi} \\ &= \boldsymbol{l_{e'} * \left(d_{out,e'} - 2 * \delta_{e'}\right) * \delta_{e'} * \pi}. \end{aligned} \tag{4.12}$$

As the parameter $\delta_{e'}$ is often not known, it is here approximated by the material information and their typical pipe wall thicknesses based on standards in residential buildings (e.g. according to Table 3 in DIN EN 1057:2010-06 for copper pipes). DIN 1988-200:2012-05 lists the main piping materials (iron-based steel and casting, copper, different types of polyethylene PE, polypropylene PP and chlorinated PVC) that are also implemented in the model.
An **insulation** layer is assumed around the pipes for hot drinking water pipes and its volume is calculated by

$$\boldsymbol{V_{e'} = l_{e'} * d_{out,e'} * \delta_{insulation} * \pi} \tag{4.13}$$

with piping insulation thickness $\delta_{insulation}$. Typical insulation material thicknesses can be found e.g. in DIN 1988-200:2012-05.
And, if visible building elements of materials have been identified in the building that occur in certain combinations with invisible building elements, the invisible building elements are assumed. E.g. if a floor covering is made of PVC and the floor construction is reinforced concrete, it is assumed that between the PVC covering layer and the reinforced concrete layer there is a layer of screed, as this combination of building elements is typical for residential buildings.

4.3.5 Calculation of building inventories

Generated building element and material inventories are twofold: (1) 'Inventory CSV/OBJ' which includes solely the recognized building elements (from CSV interface) with aggregated volume, mass and material information (also of assumed invisible building elements); and (2) 'Inventory Detail Raw Materials' which includes all building elements according to their raw material fractions (e.g. entries 'reinforcement' made of 'steel' and 'foundation matrix' made of 'concrete' instead of single entry 'foundation'). Both inventories have the same structure: building element ID, building element code DIN276, building element name, building element surface, building element volume [m³], building element mass [kg], building element material information in German and English, building element material ID, building element reference room number, minimum and maximum building element volume.
Currently, the building elements in inventories are structured according to the German standard DIN 276, that is used in architectural contexts for the structuring of building elements. In Germany, DIN 276 is the predominant building element structure in construction, retrofitting and deconstruction projects for building design, bidding processes, project planning, execution and accounting. Although BIM are increasingly applied in design and maintenance of buildings, their building element structure and information (IFC) are not used in deconstruction and

recycling of buildings yet. To enable future use of this model as well as BIM in deconstruction projects and to secure practicability, DIN 276 is used as the main data structure in an object-oriented manner to enable future BIM compatibility.

During application of the model in residential buildings, many building elements exist but the model restricts to a subset of major building element types that are considered in the following: foundations (occluded), foundation covering, walls, wall covering, floors, floor covering, ceilings, ceiling covering, openings such as windows, doors or gates, electrical equipment, water and wastewater equipment and heating equipment. Other building elements, such as roofs, staircases, balconies or other technical equipment can be integrated into the model in future extensions, especially when the model input data (CSV/OBJ interface and sensor) is able to provide such data.

4.3.6 Initial scenario construction[16]

Projects are subject to considerable uncertainties that affect schedules and projects very differently (Aytug et al. 2005 p. 91). "While it is clearly impossible (and maybe even undesirable) to explicitly address all conceivable sources of uncertainty, it is essential that the most significant are considered" for successful project execution (Aytug et al. 2005 p. 91). Models that explicitly model and discuss uncertainty causes such as material quality of several degrees are not present in literature (Aytug et al. 2005 p. 92) and not known to the author.

Sources of activity duration variability are numerous, such as imprecise estimations where activity durations are seldom precisely known and subject to estimation errors, machine breakdowns, worker absenteeism, delays due to bad weather etc. (Artigues et al. 2013 p. 176). In buildings, several potential building configurations can be anticipated, that strongly influence the necessity of activities, activity durations, resource de-

[16] Parts of this section have been published previously in (Volk et al. 2015a).

mands, and their scheduling. As in deconstruction contexts, often both exact building information and statistics on building information is lacking only reasonable expert judgments or experience and costly onsite measurements are available as a base for project planning. Exact building information leads to the deterministic case. Yet, mainly vague and imprecise information or even lacking information on likelihood is present in deconstruction contexts leading to a possible uncertainty representation via fuzzy sets or scenarios. Also, statistical information might allow deductions on underlying probability distributions of scenarios or building configurations if they are available. To the authors' knowledge, in literature these uncertainties (without probabilities of occurrences) have yet not been classified and systematically integrated in deconstruction project planning and especially not in resource-constrained multi-mode scheduling.

As demonstrated in section 4.3.1 and in Figure 4-4, eight different causes of uncertainties are identified in time and capacity planning of deconstruction projects. Projects are based on the initially available information. In deconstruction projects, this is based on the facility information that can be e.g. characterized by weight, location, radioactivity, type or materials of each structure or element (here: in the case of nuclear power plants) (Yanagihara et al. 2001 p. 194). Both project-related and building element-related uncertainties contain epistemic uncertainties that imply that the knowledge on the specification can be generated through further measurement and investigations. Especially building element-related uncertainty theoretically is measurable or knowable. However, due to time and cost restrictions of deconstruction projects these investigations are often not made in such detail[17]. Aleatoric uncertainties are not considered in this work since they are hardly quantifiable. As can be seen in Figure 4-4, properties of 'building ele-

[17] Thus, this problem can also be classified as "complicated problem" of the Cynefin framework with a theoretically known state space (scenarios). For more information on the Cynefin Framework see (Snowden and Boone 2007).

ment existence', 'element material' and 'building element volume' have strong influence on activities. Because, if the building element does not exist according to the initial assumptions, activities can be omitted or if another material is found other execution modes might be possible. E.g. a building with reinforced concrete slabs versus timber slabs leads to different activities and resource demands (durations, modes) which have to be scheduled. In the following, building elements are represented by $e' \in E'$ while building element types as 'groups of building elements' are represented by $e \in E$. As building elements' e' existence (1) (binary variable) can be modeled via building element volume (existent > 0, non-existent = 0), in the following uncertainties in material y_e (2) (discrete risk[18], categorical value), volume V_e (3) (continuous risk, numerical value), and resource demand (9) (continuous risk, integer value) represented by duration coefficients DC_j, are considered for each building element type and used for scenario construction. Thus, in this case a scenario z_k consists of different occurring parameter values of the three mentioned building-related and activity-related uncertainties based on the information available just before project start at $t = 0$ and $s = 0$.
Resulting from the finite set of building element materials, all potential building configurations are theoretically known. Thus according to (De Meyer et al. 2002), the scenario space can be classified as a decision making environment under foreseen uncertainty. Thus, complete enumeration of all scenarios with subsequent integrated capacity planning would be theoretically possible to consider all potential building configurations. Scenario construction based on complete permutation of the theoretically possible building element material leads to a combinatorial explosion of the number of scenarios[19]

$$|\boldsymbol{K}| = |\boldsymbol{E}| \times |\boldsymbol{Y_e}|, \forall \boldsymbol{e} \in \boldsymbol{E}. \tag{4.14}$$

[18] Risk classification according to (Munier 2014 p. 9f.).
[19] For scenario generation and scenario reduction with known probabilities see e.g. (Heitsch et al. 2009).

The number of created scenarios depends on the number of building element types $|E|$ and the number of potential materials $|Y_e|$ each element type can have. The described scenario construction generates e.g. more than k=10^{28} scenarios z_k with 10 different building element types that are permuted with 28 potential element types' materials Y_e (on average 4.7) per building element e. Pre-testing revealed specific material-element combinations that do not occur in reality and thus were consequently excluded from scenario construction. With a reduced number of building elements that are grouped to building element types still 914,000 scenarios were created. As each integrated capacity planning (part B) would require several minutes, so schedules cannot be calculated for all generated scenarios. And, as often plenty of scenarios overburden decision maker, further guidance in scenario techniques with regard to decision objectives are helpful and might be needed (Comes 2011 p. 38). This implies that a scenario selection or reduction is necessary to solve the problem. Scenario reduction can be performed via:

- Prioritization or excluding building elements for material variation or,
- Reduction of potential element materials Y_e or,
- Assumption of scenario probabilities (other than unitary distribution) or,
- Selection of optimistic, realistic and pessimistic scenarios.

Prioritization on building elements or excluding elements from consideration seems not a good option since also rather small building elements can induce high resource demands and activity durations. As well, for standard residential building the number of (different) building element types is very high and a reduction on few elements under consideration would not depict the problem realistically. A reduction of potential element types' materials is possible (e.g. to cluster similar types of masonry), however this also would not reduce the number of scenarios dramatically and there is a lower bound of building element property (material) differentiation necessary to describe the problem adequately.

And, a quantification of scenario probabilities is not possible due to lacking data in this field. Consequently, this model performs a subset selection of an optimistic, realistic and pessimistic material scenario that can be solved in finite time. According to Girmscheid and Busch, best and worst case scenarios have to be constructed and considered to quantify the risk impact (Girmscheid and Busch 2014 p. 65). But, scenario reduction should not reduce the range of possible outcomes and still should allow the quantification of risk impact via best and worst case scenarios. This selection and scenario construction is described in the following.

To reduce the number of scenarios k, to keep the computational effort manageable and to include uncertainties (3) and (9), the following procedure is used: Different scenarios $z_k^{Y,V,DC}$ are created via an initial building element material configuration of an examined building that is varied with other possible discrete building element volumes and duration coefficients that can be assigned to activities. Before project planning ($t = 0$, $s = 0$), a base observation $\xi_{s=0}$, e.g. during site inspection or documentation review is performed and constitutes the baseline scenario. The base observation allows deduction of the following information:

- List of detected building elements (rows) $e_{k=14,s=0}$ ($k = 14$: baseline scenario) in onsite inspection with their initially assumed material information $Y_{e,s=0}$ (columns)
- Information on building element coordinates, elements volumes $V_{e',s=0}$, their hierarchical parent information such as wall affiliation and their locations (rooms),
- General building information (year of construction, building type, etc.) and model parameters such as variation in activity durations DC_e (production rate or productivity) of building element types, material densities or standard sizes of building elements such as wall thicknesses.

Furthermore, a material variation matrix has to be given to allow building elements' material variation that is to be considered in scenario construction. Therein, the user identifies the materials with the expected building element materials $Y_{exp,e}$ for the baseline scenario. From duration coefficients $DC_{exp,m,e}$ that are estimated by experts[20] the best and worst case building element type material configurations $Y_{min,e}$ and $Y_{max,e}$ are identified via the lowest and highest average duration coefficients (production rates) that are provided by experts ($|Y_e| = 3, \forall e$). Duration coefficients are available for each mode m and for each building element type e. Then, for each building element type e, the material properties are varied (e.g. windows made of timber, steel or plastics), so that in the best case all best case materials are assumed for all building element types.

Based on these three main material scenarios, building element volumes V_e, are varied depending on their building element type. Wall volume variation follows the standard dimensions for wall thicknesses in Germany described in DIN 4172: 2015-09, that did not change since the first establishment of the standard in 1955. Minimum wall thickness is 0.115 m, maximum wall thickness is 0.36 m and interior and exterior walls are considered separately. Also, wall covering thicknesses are varied according to typical values of their type (e.g. tiles thicknesses vary between 0.01 m and 0.06 m). Ceiling and floor volume variations follow a minimum (0.07 m) and a maximum (0.3 m) thickness for slabs and likewise the coverings follow their typical building element thicknesses. Additionally, the volume of ceilings and floors (calculated by the surface plus the half wall contact area) is varied by the surface, in a way that the wall contact area is varied by the wall thickness. Foundations' volumes are varied like the volumes of floors and ceilings, except that in the case

[20] The DC were collected per literature review and three-point expert estimation and verification was provided by professionals in research projects "Immissionsschutz beim Abbruch – ISA" (Deutsche Bundesstiftung Umwelt (DBU), Az: 29014/03) and "Resource-App" (BMBF, #033R092). In future research, estimation via project comparisons and experience values could generate more appropriate values.

of their wall overlaps and protrusions the wall thickness is varied as well as the protrusion by a factor of the wall thickness. The volume variation of windows and doors is done via their frame thickness. The frame percentage of the total window or door surface [%] is not varied. The technical equipment volume variation is differentiated into the outlets' and the wirings'/pipings' volume. The outlets volumes are varied, if there are differing volumes and masses available per material. For electrical outlets, switches or distribution boxes however, the default value is no volume variation. In the case of sanitary outlets where the deviations can be large, different default outlet volumes and masses are provided by the model per outlet material. The wiring volume is varied by the length of the reconstruction wiring to its 'next' distribution point. The differing lengths result from the three different conduit zones for electrical wiring (see section 4.3.2). The parameters of cable radius or percentage of conductor material are not varied. The piping volume is varied by the pipe wall thickness parameters and the pipe diameters. Default values for typical pipe wall thicknesses and pipe diameter are provided by the model for the most common piping materials (steel, copper, PE, PVC) (see section 4.3.2). When a justified volume variation of the building element could not be researched, no volume variation is assumed as this information might be seen as certain (e.g. the volume of an electrical switch). As described above the minimum volume ($V_{min,e'}$), the expected volume of the baseline scenario ($V_{exp,e'}$), and the maximum volume ($V_{max,e'}$) ($|V_{e'}| = 3, \forall e'$) is assumed.
Furthermore, activity durations are also varied by best case ($DC_{min,m,e}$), expected case ($DC_{exp,m,e}$), and worst case ($DC_{max,m,e}$) duration coefficients per material [h/m³] that were estimated by practitioners and experts ($|DC_e| = 3, \forall e$). The duration coefficients are a possibility to include uncertainty (4) from Figure 4-4. This is considered, because activity durations are seldom precisely known and subject to estimation errors (Artigues et al. 2013 p. 176). Also, sources of activity duration variability are numerous, such as imprecise estimations, machine break-

downs, worker absenteeism, delays due to bad weather etc. (Artigues et al. 2013 p. 176) or differing productivity rates.
Based on these variations of uncertainties (2), (3) and (9) of building element materials, duration coefficients and building element volume, this leads to a total of

$$\boldsymbol{k} = \boldsymbol{Y_e} \times \boldsymbol{DC_{m,e}} \times \boldsymbol{V_{e\prime}} = \boldsymbol{3}^3 = \boldsymbol{27} \tag{4.15}$$

scenarios (see also Table 4-1). Therein, scenario 14 represents the baseline scenario with the expected building element material, the expected building element masses and expected duration coefficients. Based on the input data of an initial observation $\xi_{s=0,t=0}$ of automated building element sensing and detection linked with capturing algorithms[21] a baseline building configuration $z_{k=14,s=0}$ is captured at stage $s = 0$[22] (baseline scenario) $\xi_{s=0,t=0} = \left\{\overrightarrow{Y_{e,k,s}}, \overrightarrow{V_{e',k,s}}, \overrightarrow{DC_{e,k,s}}\right\} \forall e, e'$; $k = 14$. This is also schematically shown by Figure 4-9.
The building configuration in a scenario z_k is represented by a vector of resulting activity durations that is derived for building configuration k for all building elements e'. Further observations $\xi_{s,t}$ during project execution additionally include set of realized activities with information on already deconstructed building elements and resulting activities (columns) performed per inherent elements (rows) and a set of additionally found building elements and resulting activities depicting the current project status (see also section 4.6.3). At project start, the realization matrix R is empty as no activities have been completed yet, so that $R_{s=0,t=0} = \{\,\}$. And, the information matrix equals the initial observation vector: $I_{s=0,t=0} = \xi_{0,0}$.

[21] See section 2.3.1 for further information on building auditing and information capturing techniques and section 4.3.2 for information on themodel input data.
[22] Stage s describes a decision point in time, where a scheduling decision has to be made, either because the first baseline schedule has to be decided or the baseline schedule had become infeasible.

Recent approaches only consider and schedule this “deterministic” case (=scenario z_{14}), while in this approach also another 26 scenarios are considered (see Table 4-1). In each stage s, $k = 27$ scenarios are created describing a potential building configuration.

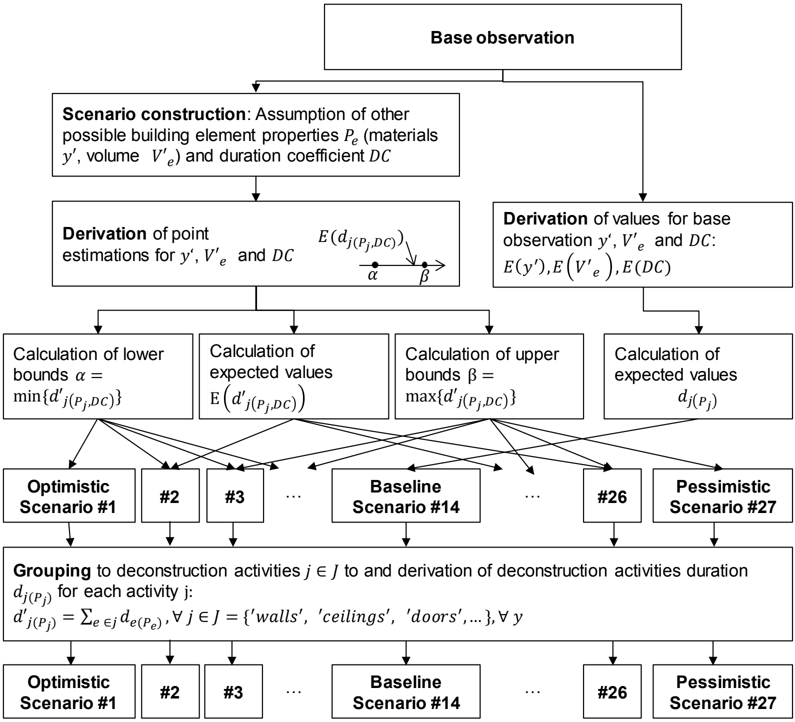

Figure 4-9: Initial scenario construction based on point estimation

A main assumption for the scenario construction is, that for all building element types the material is the same throughout the whole building. This means that respective building element materials are determined by the first found building element and its material in the building element list. E.g. different door materials of timber and steel in the same building are not differentiated in scenarios yet. However, when same building elements with different materials would be assigned to different DIN276 code numbers a further material distinction could be easily included in the model. In the following, a finite scenario and solution space is assumed; this means that all theoretically possible scenarios are assumed to be known[23].

Table 4-1: Construction/generation of 27 scenarios (scenario 1: best case scenario, grey scenario 14: baseline scenario, scenario 27: worst case scenario)

Scenario number	Building element material	Activity duration coefficients	Building element volume
1	Best material combination of all building element types	Minimum value	Minimum value
2			Expected value
3			Maximum value
4		Expected value	Minimum value
5			Expected value
6			Maximum value
7		Maximum value	Minimum value
8			Expected value
9			Maximum value
10	Expected material combination of all building element types	Minimum value	Minimum value
11			Expected value
12			Maximum value
13		Expected value	Minimum value
14			Expected value
15			Maximum value
16		Maximum value	Minimum value
17			Expected value
18			Maximum value
19	Worst material combination of all building element types	Minimum value	Minimum value
20			Expected value
21			Maximum value
22		Expected value	Minimum value
23			Expected value
24			Maximum value
25		Maximum value	Minimum value
26			Expected value
27			Maximum value

23 (Goerigk and Schöbel 2013; Scholl 2001 p. 43) show potential approaches for an infinite number of scenarios.

For simplicity, external project-related uncertainties (5) and (6) for planning and execution such as uncertain resource availabilities or site conditions are neglected in this model. To consider preemption in scheduling (7), approaches are available in literature (Afshar-Nadjafi et al. 2013; Schatteman et al. 2008; Van Peteghem and Vanhoucke 2010). Uncertainty (8) is mainly resulting from uncertainties (1), (2) and (4) and thus, it is not considered explicitly in this work. The integration of uncertainties (5), (6) and (7) might be interesting in future work in this area.

4.4 Model part B: Deconstruction project scheduling and optimization[24]

This model part schedules the deconstruction activities during the project planning process on available resources and the resulting schedules can be evaluated according to robustness criteria (model part C). Figure 4-10 shows the main steps of model part B, which include the transformation of the constructed scenarios into deconstruction activities, the grouping of these activities to deconstruction activity sets, their precedence derivation and their scheduling. This is followed by a calculation of the project costs that result from the optimal schedule in the respective scenario. In the following subsection, the single model steps are further detailed and explained.

Due to often missing, incomplete or obsolete building information and the necessity of a baseline schedule in the deconstruction context, here a baseline schedule is created according to type III (see section 3.3), which includes the anticipation and variability of the previously constructed scenarios (model part A), allows robustness evaluations (model part C) and a reactive decision making (model part D).

[24] Parts of this section have been published previously in (Volk et al. 2015a; b).

4.4.1 Activity generation from scenarios and grouping of activities to activity sets

For each scenario k, project activities j' are derived from the respective enumerated building configuration with their activity durations, precedence constraints and renewable resource demands (e.g. machines, staff, time and cost) that are necessary for the deconstruction of the building elements. Deconstruction activity derivation follows an object-oriented project work breakdown structure (WBS) (DIN 69901-3:2009-01, 4.4.2) that has been shown for deconstruction projects in Figure 2-7. The derived activities form the basis for the deconstruction optimization model that calculates an optimum schedule for the deconstruction project.

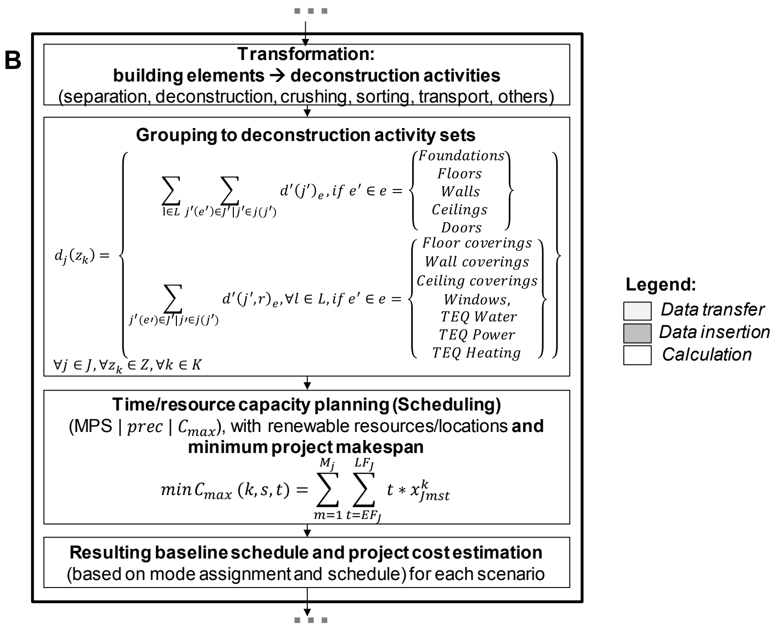

Figure 4-10: Overview on model part B

During the deconstruction process, a building element has to go through (complete) several activity types depending on the deconstruction degree. Project activities in deconstruction projects can be divided into six main and interrelated activity types that can include cleaning/decontamination, separation, dismantling, crushing, sorting and loading or transportation activities that require different amounts of constrained resources. Figure 4-11 shows the main six types and their sequential order. The deconstruction of a building element can either start (if necessary) with cleaning/decontamination, with separation from other elements or building element connectors or both before it is dismantled. Or, it can be directly dismantled. Once the building element is outside the building, three further activity types are possibly applicable. Either the building element is crushed, sorted or directly loaded for transportation.

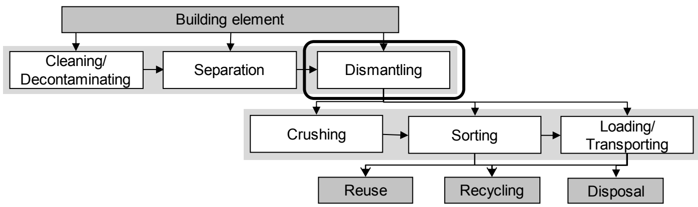

Figure 4-11: General deconstruction activity types and their sequence in processing from building element to reuse, recycling or disposal

Each activity type can be performed in different activity modes that represent differing techniques with differing resource demands. Single activities can be performed in different modes, e.g. deconstruction of a wall can be done with a hydraulic excavator, dragline excavator or pneumatic hammer. To plan all deconstruction activities adequately, a simultaneous resource and capacity planning of activities in different modes on resources has to be done (see part B, section 4.4). To create activities from the generated scenarios in this model, each building element type has to be at least assigned to one activity type ('cleaning', 'separation' etc.). For simplicity reasons and to keep the problem size manageable, each building element e is assigned to a single deconstruction activity j' including only the dismantling activity type with the derived duration and resource demands. This leads to deconstruction activities $j \in J$ that are scheduled in part B (see section 4.4). However, in real deconstruction projects, several activities per building elements of dismantling, sorting, crushing and loading activities can be necessary. Or, additional organizational activities might be included such as planning and permission processes (Bartels 2009 p. 50f.). However, this increases the number of activities and the problem size tremendously.

Furthermore, several activity modes m are considered that describe different ways of activity executions with different resource demands. Also, technical constraints are considered, when the application of specific machinery or resources is mandatory for specific materials or building elements. Via binary matrices, it is secured that only those resources are used for activities that are allowed to be applied for these activities (e.g. a ceiling cannot be deconstructed by a grinding machine). Also, the elements' material (per activity) must comply with the capabilities of the used resources in the available modes (e.g. flame-cutting cannot be applied to timber elements). Not allowed activity-mode combinations are deleted in the constraint matrix, so that these combinations are not considered by the model as potential solutions. These settings are predefined (see section 5.1.1), based on literature and expert information, but can be modified by decision maker or model user. Depending on the scenario parameter values at stage $s = 0$ and time $t = 0$, the activity duration d_{jmst} is calculated via duration coefficient $DC_{e,y}$ [h/m³] per material y, per building element e and per activity mode m. Then, this value is multiplied by the building element volume V_e so that

$$\boldsymbol{d_{j'm}} = \boldsymbol{DC_{em}} \times \boldsymbol{V_{e'}}\, \forall \boldsymbol{j'}, \forall \boldsymbol{e'}. \tag{4.16}$$

If necessary, the related mode selection is adapted or restricted according to technical feasibility. The generated k scenarios $z_{k,s}$ with differing building configurations lead to differing activity processing times and resource demands vectors that are planned in the following time and capacity planning (Part B, see section 4.4). If a building element does not exist or an activity is not performed, its activity duration and resource demands is assumed to be zero.

To solve the problem for larger buildings with a high number of technical equipment and building elements, a grouping of activities is necessary. Also, deconstruction activity durations d_j, of activities j' differ considerably in length due to the fact that both activities of deconstruction of foundations and of electrical outlets are at the same hierarchical level in the project scheduling model. To reduce the number of decision variables in the model and to keep the problem at a manageable size and solvable, activities j' are grouped into activity sets j by summation of their activity duration. E.g. the deconstruction of all technical equipment elements e such as electrical outlets, switches and distribution boxes (all electrical equipment) of a location[25] $\mathrm{l} \in L$ are grouped into a single deconstruction activity set j. There are several possibilities for grouping activities in the model that can be selected by the user:

(1) No grouping of activities and locations
(2) Grouping of activities according to same building element types and locations (rooms) in a building
(3) Grouping of activities according to trades (further grouping of building element types) and locations (rooms) in a building
(4) Grouping of activities according to building element types in the whole building

[25] A location $\mathrm{l} \in L$ can represent several spaces in construction and deconstruction projects and is modeled in location-based scheduling as a renewable resource. Locations can include rooms, building levels, outer spaces onsite, container spaces onsite etc. In the following, location is describing rooms or building levels (= subset $L_{level} \subseteq L$ of rooms of the respective level).

Grouping (1) would be the best option, as it would represent the necessary deconstruction activities at each respective location in the most detailed way. However, at a specific size of the scheduling problem this problem might not be solvable any more due to its high computational effort.

Grouping (2) gathers deconstruction activities of the same building element type per location, e.g. the deconstruction of all electrical outlets in a room are grouped to a single activity. This grouping seems reasonable to increase (and level) activity durations and to reduce the number of activities and the number of related precedence constraints. However, the activity durations often are still quite different and further activity grouping seems promising.

Therefore, grouping (3) was implemented with the aggregation according to trades per room, e.g. all electric equipment of a single room is deconstructed in a single activity. The grouping follows the precedence relations of (Schultmann 1998 p. 188) and Figure 2-8. In the approach of Schultmann, deconstruction activities related to interior fittings and technical equipment are grouped by trades (independent of their location) and ceilings, walls and floors are grouped on each building level. The interiors' deconstruction is followed by story-wise deconstruction of the structure that is clustered by building element type of ceilings, walls and floors (Schultmann 1998 p. 188), leading to 30 activities in total for a three-story building. This grouping contributes to a further decrease of the activity durations' differences.

Grouping (4) includes a quite aggregated grouping of activities without locations to a relatively small number of activities (one activity per building element type). However, even in this case the activity durations can differ that much, so that reasonable time slices (below 90 minutes) lead to "out-of-memory" errors for small problem samples (see also chapter 5).

Here, the grouping (2) is chosen due to technical and logistical reasons and due to the fact that it generates activities with durations of the same dimension. The grouped activity sets $j \in J$ are assigned to their aggregated activity durations $d_j(z_k)$ for each activity set j and each of the k scenarios in the following way:

$$\boldsymbol{d_j(z_k)} = \begin{cases} \displaystyle\sum_{\boldsymbol{l \in L}} \sum_{\boldsymbol{j'(e') \in J' | j' \in j(j')}} \boldsymbol{d'(j')_e}, \boldsymbol{if\ e' \in e} = \begin{Bmatrix} \boldsymbol{Foundations} \\ \boldsymbol{Floors} \\ \boldsymbol{Walls} \\ \boldsymbol{Ceilings} \\ \boldsymbol{Doors} \end{Bmatrix} \\ \displaystyle\sum_{\boldsymbol{j'(e') \in J' | j' \in j(j')}} \boldsymbol{d'(j', r)_e}, \forall \boldsymbol{l \in L}, \boldsymbol{if\ e' \in e} = \begin{Bmatrix} \boldsymbol{Floor\ cover}. \\ \boldsymbol{Wall\ cover}. \\ \boldsymbol{Ceiling\ cover}. \\ \boldsymbol{Windows}, \\ \boldsymbol{TEQ\ Water} \\ \boldsymbol{TEQ\ Power} \\ \boldsymbol{TEQ\ Heating} \end{Bmatrix} \end{cases}$$

$$\forall \boldsymbol{j} \in \boldsymbol{J}, \forall \boldsymbol{z_k} \in \boldsymbol{Z}, \forall \boldsymbol{k} \in \boldsymbol{K} \qquad (4.17)$$

If the activities j’ are related to the building elements of foundations, floors, walls, ceilings or doors, activity set durations $d_j(z_k)$ are aggregated per element type over the whole building (= all locations $l \in L$) to respective activity sets j. If the activities are related to the building elements windows, coverings or technical equipment (TEQ), activity set durations $d_j(z_k)$ are aggregated location-wise for all locations. As windows are often used as dust protection, they are often only partly removed room by room on those building facades were deconstruction works of the main building structure start. The remaining windows are deconstructed together with the main structure and later sorted from mineral debris. The grouping of activities is only possible, if they are related to the same building element types with the same resource demands and potential modes.

Together with the number of activities J that depending ot the activity grouping the model time slice has great influence on the number of decision variables x_{jmst} and model size. The time slice is the period between two time instances t_1 and t_2 and represents the shortest possible time periods in the model (different time aggregation levels).

The following example demonstrates this influence. The binary decision matrix has:

$$\boldsymbol{Number\ of\ rows} = \boldsymbol{2 * J + number\ of\ precedence\ relations +} \\ \boldsymbol{(R + L) * C_{max,UB}} \tag{4.18}$$

$$\boldsymbol{Number\ of\ columns} = \boldsymbol{J * M * C_{max,UB}} \tag{4.19}$$

with

J	number of activities
M	activity modes
$C_{max,UB}$	pre-defined planning horizon
R	number of resources
L	number of locations

If the differences between the activity durations of a problem are too large, the related time slices cannot be chosen adequately to keep the problem solvable in finite time. E.g. if time slices are quite detailed to depict shorter activities adequately with a problem size of up to 300 time units ($C_{max,UB}$) and a scheduling problem with 13 activities, 19 resources, 9 modes and 22 precedence relations (= case study 1, see section 5.1) leads to a binary decision matrix of 6948 x 35100 with over 243 million decision variables. With a further increasing number of activities "out-of-memory" errors might occur (see also chapter 5). Thus, time slices and the aggregation of activities is an important parameter for managing problem size and model solvability.

4.4.2 Problem description of the MRCPSP[26]

In many real-life applications of project scheduling such as deconstruction projects, an activity can be carried out in a finite number of alternative execution modes, differing in activity duration, time lags or resource

[26] Parts of this section have been published previously in (Volk et al. 2015a).

demands (Neumann et al. 2002 p. 146). Deconstruction activities can be performed with different scarce renewable resources (machines, staff) such as hydraulic excavators, hand-held pneumatic drills, chisels, crane and varying number of skilled staff and associated cost. In building deconstruction, resources can be applied to perform separation, deconstruction, crushing, sorting and loading activities that might be performed several times due to reworks e.g. in the case of contaminations (see Figure 4-11). Furthermore, technical or organizational precedence relations of activities have to be respected. And, deconstruction activities can be executed in different locations in parallel or simultaneously on the whole building site.

As discussed in section 3.4, job shop scheduling on m machines where each job has its own predetermined route (Pinedo 2011 p. 14) with precedence constraints, makespan minimization and under resource-constraints ($Jm \mid prec \mid C_{max}$) seems the most appropriate scheduling type for this application case (Schultmann 1998 p. 141f.). But as deconstruction belongs to the category of site fabrication, there are rather different modes jobs can be performed in than predetermined routes on a machine environment. And, minimization of the project makespan is the most important objective in deconstruction projects[27] (Schultmann 1998, 2003; Schultmann and Rentz 2001) where an activity can be implemented in various modes to comply with project deadlines and to avoid contractual penalties. Therefore, in this research contribution the classical multi-mode project scheduling problem ($MPS \mid prec, d_j \mid C_{max}$)[28] under resource constraints (MRCPSP), with zero-lag finish-start precedence relations and minimizing project makespan C_{max} is formulated and solved for for each scenario (notation according to (Brucker et al. 1999 p. 5; Neumann et al. 2002 p. 22). In this problem, both the mode assignment problem under capacity restrictions

[27] See (Schultmann 2003 p. 78) for a discussion on other objective functions and objective values.

[28] Notation according to (Brucker et al. 1999): ($\alpha \mid \beta \mid \gamma$) with α: machine environment, β: job characteristics, γ: objective function.

of (non-)renewable resources and the scheduling problem with precedence constraints has to be solved simultaneously (Schnell and Hartl 2013). Single-mode and multi-mode project scheduling problems are a generalization of job shop scheduling problems (Brucker 2004; Brucker et al. 1999 p. 15; Kolisch 1995; Schultmann 1998 p. 141). This problem class is NP complete (Neumann et al. 2002 p. 153; Schultmann 1998 p. 141f.).
To describe the deconstruction MRCPSP, activity sets j with durations $d_{jm_j}(z_k)$ are planned on different, limited resources r in different activity set modes m in the respective scenario z_k. Activity sets j can be seen as actions to reach a predefined aim using resources r_t in period t (Schultmann 1998; Sprecher 1994). Activity sets j are characterized by their duration (processing time), their mode, their earliest activity start time ES_j (release time), latest activity finish time LF_{j} (deadline), resource demand q_{rj} (either renewable or non-renewable) and their location demand q_{lj}. In scheduling problems, the decision variables x_{jmst} are binary and represent the completion of an activity set j in mode m in stage s at time t. Time t runs from project start $t = 0$ to project ending $t = T$. The preprocessing of time window restrictions to earliest/latest start (ES/LS) and earliest/latest finish (EF/LF) is often used to reduce the problems' solution space (see section 4.4.3).
And, the status or time of the information that was used in project planning needs to be included in model formulation. When new information arises, this can induce decision points in projects, which can be denominated with stages s. Information updates might occur in irregular time intervals. For example, regular project status updates might occur every day or every week, while irregular information updates might include unforeseeable events. Classically, stages $s = 1, \dots, S$ depict decision points in $t = 0$ and $0 < t < T$ that are characterized by milestones (fixed points in time), periodic intervals or variable points in time with completed predecessor activities and released successor activities as well as released resources that can be planned for the next period. In this case, stages are defined as variable points in time were information

updates arise and where at least one activity or resource is released for further planning. Further, it can be stated that the apriori planning process takes place at $s = 0$ and $t = 0$ and later information updates or changes occur in later project stages $s > 0$ with $t > 0$.
The possible decisions are usually constrained by limited resources r or precedence constraints $prec_j$. In deconstruction projects, technical constraints, static requirements of buildings, organizational reasons, logistic reasons and legal regulations (e.g. regarding hazardous materials) require a certain precedence of deconstruction activities or activity sets. Precedence constraints define the immediate predecessors set P_j per activity set j in a binary adjacency matrix. Precedence constraints $j_n \prec j_{n+1}$ (notation according to (Weglarz et al. 2011)) describe that predecessor activity j_n is completed before successor activity j_{n+1} can start. They are usually represented in an activity-on-node network (Hartmann and Briskorn 2010). As described by Schultmann (1998), deconstruction projects of buildings have a specific precedence structure (Schultmann 1998 p. 131) (see also sections 2.3.5.2 and 4.4.3 for details). Here, the scheduling problem is depicted as a deterministic, acyclic activity-on-node network $G = (J, prec)$ with activity sets J, single start (source) and end (sink) dummy activities. Precedence constraints may lead to a severe restriction of the solution space.
The objective of each created MRCPSP is the minimization of project makespan C_{max}. As proposed by Schultmann, dummy start and ending activities are assigned to a single mode (e.g. mode $m = 1$), which simplifies the problem and the objective function but does not restrict the solution space (Schnell and Hartl 2013; Schultmann 1998 p. 119).
The model formulation exploits at each stage s and each time t the currently available information from the previous scenario construction (part A). Thus, s and t indicate the information status of the underlying information at the time of project planning.

The following mathematical problem formulation is based on (Schultmann 1998 p. 119, 2003; Schultmann and Rentz 2001) and general scheduling literature (Schwindt and Zimmermann 2015a p. 447)[29]:

$$\boldsymbol{min\, C_{max}\,(k,s,t) = \sum_{m=1}^{M_j} \sum_{t=EF_J}^{LF_J} t * x_{Jmst}^{k}} \tag{4.20}$$

subject to:

(1) Mode assignment constraint:

$$\boldsymbol{\sum_{m=1}^{M_j} \sum_{t=EF_j}^{LF_j} x_{jmst}^{k} = 1\,, \quad for\;\; j = 1, \dots, J} \tag{4.21}$$

(2) Precedence constraint:

$$\boldsymbol{\sum_{m=1}^{M_i} \sum_{t=EF_i}^{LF_i} t * x_{im_ist}^{k} \le \sum_{m=1}^{M_j} \sum_{t=EF_j}^{LF_j} \left(t - d_{jm_j}^{k}\,(z_k)\right) * x_{jm_jst}^{k},} \tag{4.22}$$
$$\boldsymbol{for\; j = 2, \dots, J;\, i \in P_j;\; m_i \in\; M_i;\; m_j \in M_j}$$

(3) Renewable resource constraint:

$$\boldsymbol{\sum_{j=1}^{J} \sum_{m=1}^{M_j} q_{jm}^{r} \sum_{\tau=t}^{t+d_{jm}-1} x_{jms\tau}^{k} \le Q_r, \qquad for\; r \in R, t = 1, \dots, T} \tag{4.23}$$

[29] Symbols of applied decision variables and constraints are used according to common notation, e.g. in (Brucker et al. 1999; Hartmann and Briskorn 2010) and can also be found in the list of abbreviations and symbols.

(4) Renewable location constraints:

$$\sum_{j=1}^{J}\sum_{m=1}^{M_j} q_{jm}^{l} \sum_{\tau=t}^{t+d_{jm}-1} x_{jms\tau}^{k} \leq Q_l, t = 1, \dots, T; q_{jm}^{l} \in \{0, 1\}; \qquad (4.24)$$

$$Q_l = 1 \; \forall \; l \in L$$

$$\sum_{l \in L, j \in J, m \in M} q_{jm} \geq 1 \qquad (4.25)$$

(5) Activity deadline constraint:

$$x_{jmst}^{k} - d_{jm}^{k} \leq \overline{T}_j, \quad for \; \forall \; j \in J \qquad (4.26)$$

(6) Project deadline constraint:

$$\sum_{t=EF_J}^{LF_J} t * x_{Jmkst} \leq \overline{T_J} \qquad (4.27)$$

(7) Boolean decision constraint:

$$x_{jmkst} \in \{0, 1\}, for \; j = 1, \dots, J; \; m_j = 1, \dots M_j, k = 1, \dots K \qquad (4.28)$$

The mode assignment constraint (1) secures that each activity set is scheduled in exactly one mode, and thus no resource overlaps occur. Every activity set j is mandatory and scheduled exactly once and in the possible time frame. And, due to the modelling of modes, a discrete time-resource tradeoff is considered of the model, which means that the mode selection and activity set durations are dependent.

The precedence constraint (2) takes care that the activity sets to be scheduled are not scheduled outside their allowed precedence relations.

It secures, that precedence relations between activity sets and time restrictions are met, so that the successor activity set j cannot start before predecessor activity set $i \in P_j$ is completed. This is implemented by a pre-calculation of the allowed time frames that is described in detail in section 4.4.3. If the activity is not performed, its duration is $d_{jmst} = 0$.
The renewable resource constraint (3) is modeled classically. Renewable resource capacities Q_r are met for each scheduled activity set j in each scheduling period t. These include staff and machines. However, staff as a renewable resource is differentiated into two different resources according to their qualifications and skills. On the one hand, a qualified machine operator is modeled and a normal worker for less skillful activities. Staff of one of the types is assumed to be equally qualified and capable of processing all assigned activities. Furthermore, to reduce the problem, technically infeasible mode assignments with respect to the building element material are identified and excluded from the scheduling problem. And, each resource unit can only process a single activity at a time. To guarantee this, constraint (1) is formulated as disjunctive constraint to avoid unwanted resource overlaps or respective double mode assignments. In this model, resources are assumed to be constantly available in a certain amount over the whole project makespan. Although recent research focuses on varying resource availabilities and demands (Schwindt and Zimmermann 2015a p. 164), in deconstruction projects the variability of resource availability is not known or cannot be anticipated before. Thus, the model plans with constantly available resources. When resources might not be available after a certain point in time, this might be modeled via activity set deadlines, e.g. when the hydraulic excavator is needed at another site or this might induce a reactive rescheduling or deconstruction strategy shifting (see part D, section 4.6).
The renewable location constraints (4) are structurally similar to the renewable resource constraint. Renewable location resource capacities Q_l are met for each scheduled activity set j in each scheduling period t. These include locations where single activities or activity sets can take

place. In deconstruction projects and similarly to construction projects, activities can only be performed sequentially at each location inside and outside of the building. Especially in gutting and selective deconstruction as a reversed construction process, it is desirable to have staff/crews, equipment and materials "flowing" through a building. Parallel performance onsite with overlap of activities at the same location leads to blocking of ways, of storage room, of staff and of machine capacities. Thus, on limited job-sites the definition of location-based activities is helpful to schedule working teams and their resources in different parts of the site to avoid obstructing accumulations of resources or material. The location-based constraint (4) secures that there are no parallel activities at the same location, blocking each other. As a 'location' can only be used by one activity set j per period t, this means that the predecessor set i on location l has to be finished before activity set j starts to be processed at the same location. Theoretically, in large locations l (e.g. in rooms $\geq$ 30m²) several working teams could perform deconstruction activities in parallel. However, due to safety reasons onsite and model simplicity, location $l \in L$[30] is formulated as an additional specific renewable resource where one activity set is at least occupying one location at a time ($\sum_{\forall l \in L, j \in J, m \in M} q_{jm} \geq 1$) and where in every location only one activity set j can take place simultaneously ($Q_l = 1, \forall\, l \in L$). Thus, locations are modelled as renewable resources that are required for the respective activity set. According to practitioners, applied location-based management systems in construction lead to more transparency and up to 10% makespan reduction.

[30] Like activities, locations follow a given location breakdown structure (see section 3.1.1), where the building includes several levels, which themselves include rooms as the smallest location unit. Between rooms the model does not further differentiate, e.g. with respect to room type or room size.

In some projects, like deconstruction projects, the adherence to time limits is crucial, such as release times, due dates or deadlines of certain activities or a project deadline. Here, release times, due dates and deadlines are not explicitly modelled, but are integrated into the model via modification of pre-calculated earliest/latest start/finish ES_j, EF_j, LS_j, LF_j time windows of activity sets. With the activity deadline constraint (5), each project activity set finishes previous to an activity set related deadline, independent of their precedence. And, often a project deadline has to be met. With the project deadline constraint (6) the whole project finishes before project deadline $\overline{T_J}$ of the last (dummy) activity set J. Here, any occurring activity deadlines $\overline{T_j}$ $\forall j \in J$ are included into the time window calculated that precedes the problem solving (see section 4.4.3 for details).
The Boolean decision constraint (7) secures that the decision vector is modeled binary and the Boolean decision variable x_{jmst}^{k} decides if activity set j finishes in stage s at time t on mode m for each scenario k. The scheduling model is formulated with a regular[31], linear objective function as a binary, linear integer problem (BILP) with binary decision variables. The binary scheduling problem is a subcategory of MILP (mixed-integer linear program).

The scheduling model solution is on the one hand a mode assignment of each activity (resource usage) and on the other hand a schedule (list of activity starting/ completion times) with minimal project makespan (Hartmann and Briskorn 2010; Schwindt and Zimmermann 2015a p. 447). For each scenario the optimal activity modes and the optimal schedule representing the start times and resource usages of each activity set j are determined via CPLEX algorithm. The model is implemented in MATLAB R2015a and the commercial CPLEX solver from IBM ILOG Optimization Studio 12.6.2(x86-64) is used to solve the problem. The

[31] Regularity of objective functions imply that activities are to be scheduled as early as possible (Schultmann 1998 p. 127; Sprecher 1994).

used PC is a Dell Intel® Core™ 2 Duo (CPU) P4900 @2.40 GHz, with Windows 7, with 4.00 GB workspace (RAM) and a 64-bit operation system with MATLAB 2015a (64-bit) (see also chapter 5). As this is a computably challenging problem (at least NP hard) and is considerably increasing in large deconstruction projects by many location resources and activity sets, first tests were performed with smaller problem instances (see section 5.1) and later extended to larger data sets such as used in case study 2 (section 5.2). In section 4.4.4, possible solution procedures of MRCPSP and the here chosen CPLEX approach are presented and discussed.

4.4.3 Precedence relations and allowed time windows

To keep the number of variables as low as possible, the allowed time windows of the activities to be planned are previously calculated. Before solving the MRCPSP, time windows are pre-calculated where each activity set j can be scheduled in, according to its pre-determined precedence constraints. The precedence constraints follow the technical restrictions during deconstruction mentioned earlier (see 2.3.5.2). E.g. this is especially the case in planning the activities that are related to deconstructing the major building structure.

Therefore, earliest and latest start as well as earliest and latest finish of each activity are a priori calculated and an upper bound for the project makespan $C_{max,UB}$ is determined according to (Schultmann 1998 p. 117f.) by summing up the maximum duration of each activity set j of all modes $m \in M$:

$$\boldsymbol{C_{max,UB}} = \sum_{\boldsymbol{j=1}}^{\boldsymbol{J}} \boldsymbol{\max_{\forall m}\{d_{jm}\}} \tag{4.29}$$

To generate the allowed time frames for each activity, forward and backward recursion can be applied (Schultmann 1998 p. 113,118). Forward recursion generates earliest starting times (ES_j) and earliest finishing times (EF_j). Backward recursion generates latest starting (LS_j) and latest finishing (LF_j) times of each activity j' or activity set j. The earliest and latest start (ES, LS) as well as the earliest and latest finish (EF, LF) depend on the precedence relations between activities and the maximum project makespan $C_{max,UB}$. The allowed time frames in the multimode case are then calculated via forward and backward recursion for each activity set j and its predecessor activities $i \in P_j$ according to (Schultmann 1998 p. 117):

Forward recursion:

$$\boldsymbol{ES_1 = 0} \tag{4.30}$$

Earliest start of the first activity set is at time $t = 0$.

$$\boldsymbol{EF_1 = min\{d_{1m} |\, m \in M\}} \tag{4.31}$$

Earliest finish of the first activity set is defined as the minimum duration of all modes m.

$$\boldsymbol{ES_j = max\{ES_i + min\{d_{im} |\, m \in M\} \mid i \in P_j\}}, \tag{4.32}$$

for $j = 2, \ldots, J$

Earliest start of activity set j is defined as the earliest finish time of all predecessor activity sets P_j.

$$\boldsymbol{EF_j = max\{EF_i | i \in P_j\} + min\{d_{jm} | m \in M\}}, \tag{4.33}$$

for $j = 2, \ldots, J$

Earliest finish of activity set j is defined as the maximum of earliest finish of predecessor activity sets $i \in P_j$ plus the minimum duration of activity set j in mode m.

Backward recursion:

$$\boldsymbol{LS_J = C_{maxUB} - min\{d_{Jm} | m \in M\}} \tag{4.34}$$

Latest start of the last activity set J is defined as the upper bound project makespan $C_{max,UB}$ minus the minimum duration of activity set J.

$$\boldsymbol{LF_J = C_{maxUB}} \tag{4.35}$$

Latest finish of the last activity set J is defined as the upper bound project makespan due to the dummy duration of J.

$$\boldsymbol{LS_i = min\{LS_j | j \in S_i\} - min\{d_{im} | m \in M\}}, \tag{4.36}$$

for $\forall i = 1, \dots, J-1$

Latest start of activity set i of all successor activities $j \in S_i$ minus minimum duration of predecessor activity set i.

$$\boldsymbol{LF_i = min\{LF_j - min\{d_{jm} | m \in M\} \mid j \in S_i\}}, \tag{4.37}$$

for $\forall i = 1, \dots, J-1$

Latest finish of activity set i is defined as the latest finish of successor activity sets j minus their minimum duration.

Furthermore, according to precedence relations there are several relations to be defined that have to be valid:

$$\boldsymbol{ES_j = max\{EF_i | i \in P_j\}}, \tag{4.38}$$

for $j = 2, \dots, J$

Earliest start of activity set j is defined as latest earliest finish of all predecessor activity sets i (earliest start of activity set j cannot take place before all predecessors i are finished).

$$\boldsymbol{EF_j = ES_j + min\{d_{jm} | m \in M\}}, \tag{4.39}$$

for $j = 1, \dots, J$

Earliest finish of activity set j cannot take place before its earliest start plus its minimum duration.

$$\boldsymbol{LF_i = min\{LS_j | j \in S_i\}}, \tag{4.40}$$

for $i = 1, \dots J-1$

Latest finish of predecessor i is defined as the earliest latest start of all successors j (latest finish of predecessor i cannot take place after latest start of all successors j).

$$\boldsymbol{LS_i = LF_i - min\{d_{im} | m \in M\}}, \quad (4.41)$$
for $i = 1, \dots, J$
Latest start of predecessor i is defined as its latest finish minus its minimum duration.

Independently of the project stage s, these rules apply to all (remaining) project activities or activity sets that have to be scheduled. The described time frames are used in section 4.4.1 to simultaneously plan activities and resources. However, the generated time frames of ES_j, EF_j, LS_j, and LF_j disregard resource constraints.

4.4.4 Problem classification, solution methods and computational effort

As the classical RCPSP is a generalization of the job shop scheduling problem, it belongs to the class of combinatorial[32] problems (Schultmann and Rentz 2001) and the problem class of strongly NP-hard problems (Artigues et al. 2008 p. 23; Blazewicz et al. 1983; Hapke and Slowinski 2000; Igelmund and Radermacher 1983; Schultmann 1998 p. 141). "For more than one non-renewable resource the problem of finding a feasible solution is already *NP*-complete" (Kolisch 1995; Schwindt and Zimmermann 2015a p. 446). Furthermore, the problem formulation is linear and binary, being a sub problem of integer linear problems with a finite number of decision variable values and a finite set of parameter assignments.
In literature, several measures are used to classify or rate a scheduling problem. Most important indices are the resource factor RF and the resource strength RS that are both defined on the interval $RF, RS \in [0;1]$ (Bartels 2009 p. 104; Neumann et al. 2002 p. 104).

[32] "When n non-dummy activities can be scheduled in m different modes, this results in a total of m^n possible mode alternatives, each of which can be seen as an instance of the basic RCPSP" (Deblaere et al. 2008 p. 20).

The indicators are defined by (Kolisch 1995 p. 54f.) for the multimode case as:

$$\boldsymbol{RF} = \frac{\mathbf{1}}{(\boldsymbol{J}-\mathbf{2})*|\boldsymbol{R}|}\sum_{j=2}^{J-1}\sum_{m=1}^{M}\sum_{r\in R}\boldsymbol{\delta}(\boldsymbol{q_{jmr}}),\ \forall \boldsymbol{r} \in \boldsymbol{R}, \tag{4.42}$$

with

$$\boldsymbol{\delta}(\boldsymbol{q_{jmr}}) = \begin{Bmatrix} \mathbf{1},\ \boldsymbol{for}\ \boldsymbol{q_{jmr}} > \mathbf{0} \\ \mathbf{0},\ \boldsymbol{for}\ \boldsymbol{q_{jmr}} = \mathbf{0} \end{Bmatrix}$$

$$\boldsymbol{RS} = \frac{\boldsymbol{Q_{rt}}-\boldsymbol{Q_r^{min}}}{\boldsymbol{Q_r^{max}}-\boldsymbol{Q_r^{min}}},\ \forall \boldsymbol{r} \in \boldsymbol{R}, \forall \boldsymbol{m} \in \boldsymbol{M}, \tag{4.43}$$

with

$$\boldsymbol{Q_r^{min}} = \boldsymbol{max_{j\in J}}\ \boldsymbol{min}\{\boldsymbol{q_{jr}}\ \mid \mathbf{1} \le \boldsymbol{m} \le \boldsymbol{M}\} \tag{4.44}$$

and

$$\boldsymbol{Q_r^{max}} = \boldsymbol{max_{t\ge 0}}\ \boldsymbol{min_{m=1,\dots M}}\{\boldsymbol{m} \mid \boldsymbol{q_r}(\boldsymbol{ES},\boldsymbol{t})\}, \forall \boldsymbol{r}. \tag{4.45}$$

Q_r^{min} and Q_r^{max} define the lower and upper bounds for resource capacity. RF describes which share of renewable resources is used on average for a single activity (Bartels 2009 p. 104). $RF = 0$ indicates that an activity does not required any resources, while $RF = 1$ means that the activity demands all resources at once. RS is a measure for the scarcity of renewable resources, where a low value indicates a high restriction of the resource capacity. $RS = 0$ indicates that at least one activity requires the whole capacity of a resource (Zimmermann et al. 2006 p. 307). Scheduling problems with a low RS value are rather difficult to solve (Zimmermann et al. 2006 p. 307). Another characterization is the restrictiveness $RT \in [0,1]$ which depicts the degree of parallel activities in an acyclic project network (Bartels 2009 p. 104; Zimmermann et al. 2006 p. 307) and it is defined according to (Neumann et al. 2002 p. 102f.) as:

$$\boldsymbol{RT} = \mathbf{1} - \frac{\boldsymbol{log\,\Pi}}{\boldsymbol{log\,j}!}, \tag{4.46}$$

with

$\boldsymbol{\Pi}$**:** number of all possible sequences of real activities j.

This is often approximated by the order strength OS that is defined as:

$$\boldsymbol{OS} = \frac{\sum_{i,j \in J} \rho_{i,j} - 3 * (n+1)}{n * \frac{n-1}{2}}, \tag{4.47}$$

with

$$\boldsymbol{\rho_{i,j}} = \begin{Bmatrix} \mathbf{1}, \boldsymbol{if\ i = j\ or\ i \prec j} \\ \mathbf{0}, \boldsymbol{otherwise} \end{Bmatrix}, (\boldsymbol{i}, \boldsymbol{j}) \in \boldsymbol{J}$$

RT increases with higher parallelism of activities. In the following case studies (see chapter 5) these indices are used to characterize the MRCPSP scheduling problem.

Solution procedures of RCPSP are numerous and can be differentiated into exact and heuristic approaches (see Table 4-2) (Corsten et al. 2008 p. 178; Domschke and Drexl 2007 p. 127f.)[33]. Exact methods are able to find the global optimum objective value for RCPSP, while heuristics do not always find a global optimum solution, but might get lost in local optima and miss the global optimum value. Therefore, exact methods provide optimal solutions, while heuristics find a near-optimal solution with lower solution quality.

Exact methods are divided into (1) decision tree approaches, (2) cutting plane approaches and (3) combinations (see Table 4-2) (Domschke and Drexl 2007 p. 128). Exact approaches include the branch-and-bound

[33] Overviews on solution methods can be found in in (Brucker et al. 1999; Deblaere et al. 2008 p. 2; Domschke and Drexl 2007; Hartmann 1999; Pinedo 2011 p. 431ff (Chapter 16)).

algorithm with the partial enumeration of schedules, hybrid approaches with combination of constrained programming and satisfiability testing (SAT) or lower bounds (Demeulemeester and Herroelen 2009 p. 29). Generally, branch-and-bound algorithms exclude feasible solution areas in the enumeration tree from further search for optimal solutions that do not lead to the optimal solution (e.g. due to bounding or cutting rules) (Schultmann 1998 p. 147f.). Schwindt and Zimmermann describe the currently best available branch-and-bound and branch-and-cut approaches for MRCPSP that can be found in literature (Schwindt and Zimmermann 2015a pp. 449–454). But, exact approaches are only applicable up to a problem size of 50 activities (Domschke and Drexl 2007 p. 119). Exact methods are able to solve (mixed) integer linear optimization problems (Nickel et al. 2014 p. 173), but the branch-and-bound efficiency heavily relies on the formulation of construction and search procedures (Demeulemeester and Herroelen 2009 p. 29). However, branch-and-bound algorithms come to their limits when it comes to very large problems such as the MRCPSP with many activities to be planned (Xu and Feng 2014). Thus, for real problems with a larger number of activities, it is advisable to implement heuristics that are able to cope with the problem size in reasonable time (Corsten et al. 2008 p. 178; Domschke and Drexl 2007 p. 119).

Heuristic techniques are divisible according to (Domschke and Drexl 2007 p. 128) in (4) opening procedures to calculate a (first) feasible solution; (5) local search and improving procedures to improve a given feasible solution; (6) incomplete exact methods like partly enumerating branch-and-bound, and (7) combinations of the previous methods. Furthermore, there are a plethora of dispatching rules such as priority based heuristics (Chtourou and Haouari 2008; Corsten et al. 2008 p. 178) or presorting strategies e.g. according to weighted shortest expected processing time (WSEPT), earliest due date (EDD) or longest expected processing time (LEPT) sequences (Pinedo 2011 pp. 44–47, 270, 353, 376–382). Schwindt and Zimmermann describe the state of the art heuristics that are applied for MRCPSP (Schwindt and Zimmermann 2015a pp. 458–470).

Table 4-2: Classification of possible solving methods and found implementations[34]

<table>
<tr><th>Optimization / Exact solution</th><th>Heuristics</th></tr>
<tr><td rowspan="2">Decision tree approaches
• complete enumeration,
• partly/limited enumeration via branch-and-bound (Afshar-Nadjafi et al. 2013; Nickel et al. 2014 p. 193ff.; Schultmann 1998; Sprecher 1994; Zimmermann et al. 2006 p. 208f.),
• dynamic optimization/programming (Nickel et al. 2014 p. 289ff.)</td><td>Opening procedures</td></tr>
<tr><td rowspan="2">Local search and improving procedures
• (pareto) simulated annealing (PSA) (Hapke and Slowinski 2000; Pinedo 2011 pp. 382–388) ,
• taboo search (Pinedo 2011 pp. 382–388),
• genetic algorithms (GA) (Kellenbrink and Helber 2013; Xianggang and Wei 2010; Xu and Zhang 2012)
• (light) beam search (LBS) (Pinedo 2011 pp. 400–402)
• particle swarm optimization (PSO) (Xu and Feng 2014)
• ant colony optimization (ACO) (Pinedo 2011 pp. 391–393)</td></tr>
<tr><td>Cutting plane approaches
(Domschke and Drexl 2007 p. 127)
• Gomory approach (Nickel et al. 2014 p. 201ff.)
• Bender approach</td></tr>
<tr><td>Combinations
• branch-and-cut (Nickel et al. 2014 p. 208)</td><td>Incomplete exact methods
• partly enumerating branch-and-bound
• machine-based decomposition methods (shifting bottleneck (Pinedo 2011 pp. 193–207))
• job-based decomposition methods
• time-based decomposition methods (rolling horizon (Pinedo 2011 pp. 402–407))</td></tr>
<tr><td></td><td>Combinations</td></tr>
</table>

Advantages and disadvantages of mentioned exact methods and heuristics are widely discussed in OR literature and can be found in the pro-

[34] According to (Artigues et al. 2008 p. 151f.; Domschke and Drexl 2007 p. 127f.; Kolisch 1995 p. 66ff.; Nickel et al. 2014 p. 209ff.; Pan et al. 2001).

posed references (Artigues et al. 2008 p. 151f.; Domschke and Drexl 2007 p. 127f.; Pan et al. 2001). In this research contribution, the IBM ILOG CPLEX solver is used that is based on the exact branch-and-cut algorithm. However, for the majority of dynamic and stochastic problems, no powerful solving methods are available yet and are thus often simulated (and not optimized) (Neumann and Morlock 2002).

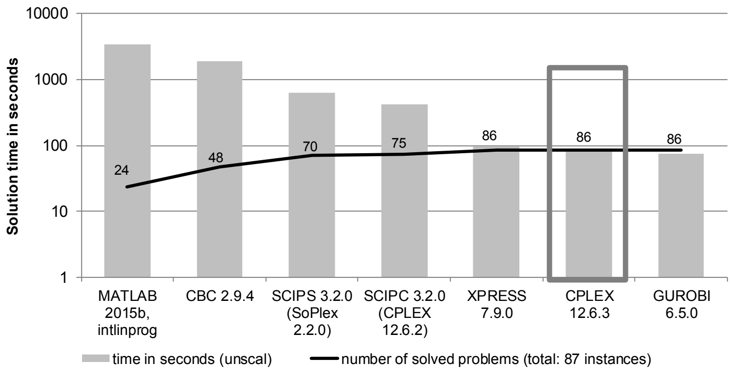

Figure 4-12: Comparison of commercial (MATLAB, SCIPC, XPRESS, CPLEX, GUROBI) and non-commercial (CBC, SCIPS) solver for linear mixed-integer problems (MILP)[35]

As the formulated problem in this research contribution is a binary (= integer) linear problem, exact methods such as branch-and-bound methods are able to solve this formulated problem (Nickel et al. 2014 p. 193). The deconstruction scheduling and optimization tool is implemented in MATLAB R2015a (64-bit) programming software of Mathworks Inc. The here used CPLEX solver of IBM ILOG Optimization Studio 12.6.2 solves mixed integer (MILP) and binary (BILP) problems exactly after a comprehensive pre-analysis using a very general and robust algorithm based on branch-and-cut (IBM 2016). Branch-and-cut is based

[35] Data source: (Mittelmann 2016).

on splitting the original problem into several sub problems and searching in each easier sub problem for the optimal solution. Thus, it belongs to the class of decomposition approaches. Via bounds for the optimum objective value, feasible but non-optimal solutions are excluded from further search (Nickel et al. 2014 p. 193). The current planning horizon $C_{max,UB}$ of the model is determined by the pre-processing of the timely precedence constraints (see section 4.4.3) and eventually divided into time slices to reduce the model size and to secure solvability.
Figure 4-12 shows main commercial and non-commercial solver for exact solving approaches of linear, mixed-integer problems together with their computational effort (sec) and the instances solved. The CPLEX solver used in this research contribution has a very good performance with regard to solution time and solution quality compared to the other available solvers.

4.4.5 Critical path and buffer calculation

The critical path determines the minimum project makespan, sometimes also referred to as critical chain (Herroelen and Leus 2004 p. 1604). To identify a critical path, the total float, free float and independent float can be calculated for each activity set j. Activity sets with zero float are socalled “critical activities” and indicate the critical path (Corsten et al. 2008 p. 129; Nickel et al. 2014 pp. 158–165). To calculate buffer times, the following formulations are applied in the model according to (DIN 69900:2009-01, 3.31, 3.21, 3.90) and (Corsten et al. 2008 p. 129; Nickel et al. 2014 pp. 158–165). The total float TF_j of each activity set j is defined as the time span between earliest (ES_j) and latest start (LS_j) of an activity set:

$$\boldsymbol{TF_j = LS_j - ES_j} \quad (4.48)$$

The free float is defined as the time span an activity set j can be shifted from its earliest start without affecting the earliest start of other activities (i=successors):

$$\boldsymbol{FF_j = min_i\{ES_{ij}\} - EF_j} \tag{4.49}$$

The independent float is defined as the time span an activity set j can be shifted or prolonged if its predecessors start as late as possible and its successors start as early as possible (i=successors, n=predecessors)

$$\boldsymbol{IF_{jn} = max\{0, min_i\{ES_{ij}\} - max_n\{LF_{jn}\} - d_j\}} \tag{4.50}$$

Here, total float, free float and independent float are calculated for each activity and each scenario to identify the critical path. This information can be useful for decision makers with respect to the selection of robust deconstruction strategies.

4.4.6 Project accounting and cost estimation

As in operative planning the economic consequences of each scheduling decision cannot be quantified (Corsten 1994 p. 419; Daub 1994 p. 68), the alignment of operational planning problems on project costing is often associated with considerable difficulties (Schultmann 1998 p. 123). Thus, operational planning often relies on resource and capacity planning and a resulting cost derivation, that also supports the avoidance of penalty cost due to late completion and a rapid release for other projects (Schultmann 1998 p. 123). In conformance with literature, in this model the main focus lies on project makespan minimization. Project cost are considered minimal as a result from project makespan minimization. Thus, after all mode assignments (and resource assignments) are made and deconstruction activities are scheduled, the used resources can be accounted and the project cost can be calculated.

During project planning, decision makers are interested in the internal accounting and especially in the management accounting of project activities. Management accounting can be separated into two fields: cost estimation (pre calculation) and costing (post calculation), that are described in the following:

Cost estimation includes the calculation of the expected single (variable) cost and overhead (fixed) cost for the individual make-to-order (production, construction or) deconstruction project with its special competition and bidding processes. When the project is scheduled with minimum project duration, direct (variable) cost of activities and services, indirect (fixed) costs and other costs per project (Corsten et al. 2008 p. 186f.; Girmscheid and Motzko 2013 pp. 165–247; Leimböck et al. 2015 pp. 20–24) can be estimated. Fixed costs are given by the cost for the required resources over project makespan regardless of their deployed hours in the project such as cost for offices, secretary and administration, repairing units etc. These apply for the decision maker (deconstructor) despite any project activity. Variable cost are based upon deployed hours of the resources in the project and on the consumables' of the resources or are calculated based on the found building elements in the deconstruction object[36]. The variable cost can be further differentiated into the following types: labor cost, raw materials and supplies cost, equipment cost, external subcontractor cost. Cost for raw material is not considered here, as raw materials are only rarely used on deconstruction projects, e.g. explosives for the blasting deconstruction technique which is not considered in this model. And, cost for subcontractors are not considered here as the project is assumed to be a single-contractor project. For multi-contractor projects the cost for the outsourced activities are subsumed under this category. In this model, the direct, variable costs C_{var} are determined by cost parameters per activity j', and their used resources (staff and machinery with equipment). The variable

[36] See also (Girmscheid and Motzko 2013 p. 212ff) for a detailed breakdown structure and calculation for machinery and equipment cost.

activity cost $C_{var,j'}$ based on its labor demand, machinery demand and equipment resource demand is calculated as follows:

$$\boldsymbol{C_{var,j'(e')}} = \sum_{r \in R} \sum_{m \in M} \left[\left(\frac{\boldsymbol{RV_r + SC_r + IR_r}}{\boldsymbol{8760 * SL_r\,[years]}} \right) [\frac{\boldsymbol{EUR}}{\boldsymbol{h}}] * \sum_{j' \in J'} \boldsymbol{d_{j'mr}\,[h] * q_{j'mr}} \right] \tag{4.51}$$

with

$C_{var,j'(e')}$: Variable cost of activity j' related to building element e' [EUR]

$d_{j'mr}$: Duration of activity j' on resource r in mode m in the optimal schedule [hour]

$q_{j'mr}$: Resource demand of activity j' in mode m of resource r [#] in the optimal schedule

RV_r: Replacement value of resource r based on the depreciation rate [EUR]

SL_r: Expected service life time of resource r [years]

SC_r: Supply cost for operational means [EUR]

IC_r: Interest cost based on the interest rate [EUR]

The first term in parentheses describes the resource cost per time unit [hour] based on its replacement value, the supply cost for operational means and the interest cost for the initial investment. This value is multiplied with the required quantity of each resource per activity and with the duration of activity according to the assigned mode m.

In practice, the value $C_{var,j'}$ is often rearranged and calculated on the base of building element units. So, instead of the activity duration the units of building elements in the building and the velocity of the assigned mode are applied. Then, for simplicity, the resource cost and the mode velocity are aggregated to the cost factor c_{mr} of resource r in mode m. Then, c_{mr} is stored in an experience value database. For calculation, then only the building inherent building element dimensions are multiplied with an aggregated cost factor $c_{e\prime mr}$:

$$\boldsymbol{C_{var,j\prime(e\prime)}} = \sum_{\boldsymbol{r \in R}} \sum_{\boldsymbol{m \in M}} \boldsymbol{c_{e\prime mr}} * \boldsymbol{U_{e\prime}}\ [\boldsymbol{m^3, m^2, m, piece}] \tag{4.52}$$

$$\boldsymbol{c_{e\prime mr}} = \left(\frac{\boldsymbol{RV_r + SC_r + IR_r}}{\boldsymbol{8760 * SL_r\ [years]}}\right)\left[\frac{\boldsymbol{EUR}}{\boldsymbol{h}}\right] * \boldsymbol{v_m}\left[\frac{\boldsymbol{h}}{\boldsymbol{m^3}}, \frac{\boldsymbol{h}}{\boldsymbol{m^2}}, \frac{\boldsymbol{h}}{\boldsymbol{m}}, \frac{\boldsymbol{h}}{\boldsymbol{piece}}\right] * \boldsymbol{q_{j'mr}} \tag{4.53}$$

with

$c_{e\prime mr}$: Cost factor for building element e’, depending on units of building element e’, mode m and resource r

$U_{e\prime}$: Units of building element e' that are deconstructed in activity j’ [m³, m², m, piece]

v_m: Velocity of the assigned mode m per building element unit [h/m³, h/m², h/m, h/piece]

Or, a less detailed cost estimation via cost factor $c_{U(e')}$ ist also done without differentiation of the applied resources and modes:

$$\boldsymbol{C_{var,j\prime(e\prime)}} = \sum_{\boldsymbol{r \in R}} \sum_{\boldsymbol{m \in M}} \boldsymbol{c_{U(e')}} * \boldsymbol{U_{e\prime}}\ [\boldsymbol{m^3, m^2, m, piece}] \tag{4.54}$$

with

$c_{U(e')}$: Cost factor for building element e’ depending on units of building element e’

The first approach is often used in cost accounting for staff, resources and operating supplies cost (see also (Schultmann 1998 p. 86f., 125f.) and is especially applied when new types of projects are calculated e.g. with new resources or new objects (building or infrastructure types). For known (regular) deconstruction activities with already assessed building elements and resources, often the simplified calculation is performed. This and further analysis on cost drivers is also sometimes referred to as activity-based costing (Kao et al. 2006 p. 385f.). Practitioners usually pre-calculate project cost with the found, building-inherent elements. Then, costs are quantified according to the respective dimensions of the building elements as described in DIN 18459:201508 section 0.5 either by EUR/m³, EUR/m², EUR/m or EUR/piece. And, variable costs are structured according to the commonly used DIN 276-1:2008-12 for building construction costing that follows a hierarchical structure of building elements.

As the scheduled activity sets j consist of the deconstruction of a group of building elements e' and their related deconstruction activities j'(e'), the activitiy set costs $C_{var,j}$ are calculated by further aggregation of the variable cost of activities j' per set ($j'(e') \in J'|j' \in j(j')$) as follows:

$$\boldsymbol{C_{var,j}} = \sum_{\boldsymbol{j'} \in \boldsymbol{j}(\boldsymbol{j'})} \boldsymbol{C_{var,j'}} \ , \forall \boldsymbol{j} \in \boldsymbol{J} \tag{4.55}$$

with

$C_{var,j'}$: Cost of each activity j' related to building element e'
[EUR/m³, EUR/m², EUR/m, EUR/piece]

The aggregation assumes only the summation of equal building elements (e.g. all windows of a room) which does not have any influence on the mode assignment as described in section 4.4.1.

In general, the way of the cost estimation in deconstruction projects depends on the available experience values of the decision maker. In this model, $C_{var,j}{}'$ is calculated in both ways. When $C_{var,j}{}'$ is calculated with RV, SC and IC, the labor costs [EUR/h] are calculated based on the current standard wages in Germany for machinery operator and workers in the deconstruction industry. The equipment costs [EUR/h] are calculated by their depreciation value based on the current replacement value, the interest cost and repair cost for the carrier machinery, attachment and accessory equipment for the time it is used in the project. Cost-accounting depreciation for resources such as excavators, attachments and accessory equipment is considered with a linear depreciation rate for each resource over the expected service life in years and is based on the replacement value. An overview on typically applied machinery in deconstruction projects can be found in (Toppel 2004 pp. 95–100).

In this model, the variable deconstruction costs are restricted to the quantification of deconstruction cost and recycling or disposal cost related to building elements. Disposal costs and recycling revenues are based on actual prices of respective waste fractions as well as raw material and recycling material prices (see also chapter 5).

Furthermore, in project accounting indirect cost (overhead) are calculated for each project. This can include local onsite cost or general administration cost. Local onsite cost can consist in cost for the erection of the deconstruction site, e.g. transportation and installation of equipment, trailer, cabins or containers, assembly and disassembly of water and energy supply systems, access and security measures, storage and work spaces, or other costs such as the planning and controlling onsite (Leimböck et al. 2015 p. 22). General administration cost can include e.g. office cost, insurances or lawyer cost. Fixed costs are calculated as follows:

$$\boldsymbol{C_{fix} = c_{ind,T_J} * T_J + C_{other}} \tag{4.56}$$

with

c_{ind,T_J}:	Cost factor for indirect project cost dependent on project makespan T_J [EUR/h]
T_J:	Project makespan [h]
C_{other}:	Other project cost [EUR]

Fixed project costs accrue in each project at a fixed cost factor, not depending on the applied resource onsite, the schedule or the inherent building elements onsite. Other project costs depend on accessibility of the site and the need of site preparation, the size of the project site and neighboring areas, it is difficult to quantify these costs.
Total project costs are calculated as the sum of both components of $C_{var,j}$ and C_{fix}, where the variable costs are directly depending on the activity durations, whereas indirect cost are monotonically increasing over project makespan (Schultmann 1998 p. 125):

$$\boldsymbol{C_{total}} = \sum_{\forall \boldsymbol{j} \in \boldsymbol{J}} \boldsymbol{C_{var,j}} + \boldsymbol{C_{fix}} \tag{4.57}$$

Although the application of different resources might have an effect on the indirect project cost, main issues such as security measures, water or energy supply, installation of onsite devices, containers etc. can be assumed equal in the same project. Only the variable costs are differing according to the mode assignment, the resource usage and the schedule. Thus, in this research contribution, the indirect costs are not calculated and further considered. This leads to the fact that the costs for the deconstruction project are proportional to the duration of the activities in their assigned mode m (Schultmann 1998 p. 125f.).
During or after the project, the costing is done with the realized values in the project. In deconstruction projects, additional services can be charged extra and thus they are calculated separately. As project control is not in the focus of this work, cost performance measure metrics e.g. from (ex post) earned value management (EVM) (see (Munier 2014 p. 2)) with total project cost, cost variance, schedule variance, cost performance index, schedule performance index or estimate at completion cost are not considered here.

4.5 Model part C: Identification and selection of robust deconstruction strategies[37]

Figure 4-13 gives an overview on the following model part C. The first subsection is dedicated to the transformation of the optimum deconstruction baseline schedules that where generated by the MRCPSP problem solver in model part B for each scenario into deconstruction strategies (section 4.5.1). Then, the resulting deconstruction strategies are applied to each scenario (4.5.2). And, each deconstruction strategy is evaluated (4.5.3) based on adequate robustness measures that meet the decision makers' risk preferences. This results in a ranking of deconstruction strategies and the identification of the optimum deconstruction strategy in all scenarios (robust deconstruction strategy).

4.5.1 Transformation of schedules into strategies

In this step, the generated optimum schedules $Sched^*(z_k)$ of each scenario z_k are transformed into deconstruction strategies $\Pi(z_k)$. Aim is, to find an 'optimal' deconstruction strategy $\Pi^*(z_k)$ that performs as good as possible in all scenarios.

In MRCPSP, schedules are an assignment of activity sets j to starting or ending times $t \in T$ and to modes $m \in M$. The starting and ending times of activity sets have a sequence or precedence on each resource $r \in R$. The mode assignments and the activity sets itself provide information on their resource usage of resources $r \in R$ and their location occupation of locations $l \in L$:

$$\boldsymbol{Sched}^*(\boldsymbol{z_k}) \rightarrow \boldsymbol{T}, \boldsymbol{M} \rightarrow \boldsymbol{T}, \boldsymbol{R}, \boldsymbol{L}. \tag{4.58}$$

[37] Parts of this section have been published previously in (Volk et al. 2015a; b).

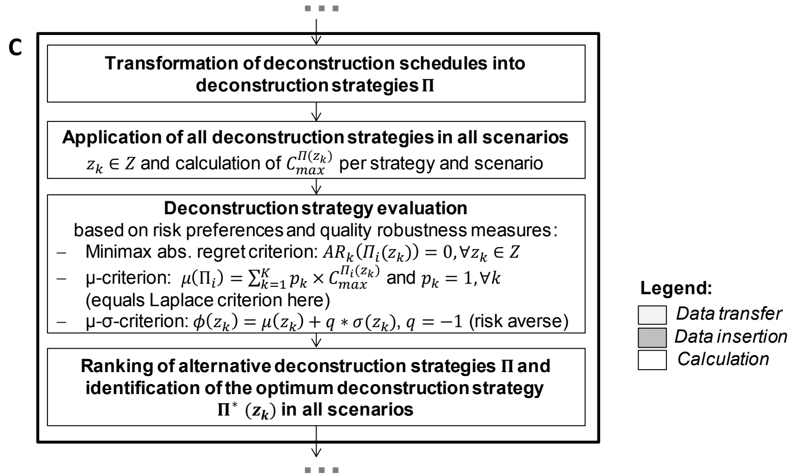

Figure 4-13: Overview on model part C

As the starting or ending times can be subject of uncertainty, the resulting deconstruction strategies $\Pi(z_k)$ only include the resource and location assignment and the sequence of the activities sets j on the respective renewable resources r and locations l. To simplify the problem, the locations are neglected in the optimal deconstruction strategies. As they constitute only 'additional' renewable resource to the classical resources, this is a feasible way to reduce the problem size without altering the solution:

$$\boldsymbol{Sched^*(z_k) \rightarrow T, M \rightarrow T, R, L \rightarrow Seq(j, R, L) \rightarrow Seq(j, r): j_\alpha \prec j_\beta, \forall j_\alpha, j_\beta \in J, \forall r \in R = \Pi^*(z_k).} \tag{4.59}$$

These resource assignments and sequences are used for the following application of the 'optimum' deconstruction strategies $\Pi^*(z_k)$ of each scenario z_k on all scenarios Z to evaluate their overall performance.

4.5.2 Application of deconstruction strategies in scenarios

The identified optimal deconstruction strategies $\Pi^*(z_k)$ are applied to all scenarios Z and the respective project makespan of the deconstruction strategy is calculated per scenario $C_{max}^{\Pi^*(z_k)}$.
In the model, a list-scheduling heuristic is performed in this step that respects sequences of activity sets j' (precedence), the resource assignment and the resource constraints. The classical list scheduling algorithm tries to schedule activities from a pre-defined activity list onto available resources and is described in the following. Every time, an activity is released (all predecessors according to the precedence relations are already completed) or when a resource becomes idle, the list scheduling algorithm tries to schedule the next activity on the list on the idle resource (Neumann 1998 p. 5). In this multi-resource list scheduling algorithm, each iteration is determined by the resource with the minimum actual time, or which is the next idle resource. The activities on the list can be sorted according to priority, according to any other order or randomly. In this case, the sequence of the activities on the list(s) is predetermined by each applied deconstruction strategy $\Pi^*(z_k)$. The algorithm terminates when the list is empty.
The scheduling of the activity sets follows the given 'optimal' deconstruction strategies $\Pi^*(z_k)$ per scenario z_k and is based on the given resource assignment of the optimal MRCPSP schedule. Helpful in the scheduling of the 'optimal' strategies on all scenarios is, that the allocation of activities to resources is already done, as well as the order of the activities on the resources is known. This allows the application of the list scheduling heuristic to determine the schedule $Sched(z_k, Seq(j,r))$ (start and completion times of the activities and activity sets) according to their precedences. When the list-scheduling algorithm was applied, the project makespan C_{max} of every optimal deconstruction strategy $\Pi^*(z_k)$ in every scenario z_k is known with $C_{max}^{\Pi^*(Z)}$. Then, deconstruction strategies $\Pi^*(z_k)$ can be assessed and compared with each other regarding their performance in all scenarios and their robustness criteria can be

calculated. These allow decision makers to decide on the most promising, best performing deconstruction strategy $\Pi^*(Z)$ over all considered scenarios Z. This is described in the next section 4.5.3.

4.5.3 Deconstruction strategy evaluation and selection based on risk preferences and robustness measures

In order to find project schedules that perform well under uncertain project conditions, the concept of robustness was developed to especially increase preparedness for the worst-case. Robust planning evaluates alternative strategies with robustness criteria and decision makers' risk preferences (Scholl 2001 p. 139f.)[38]. Quality robustness aims at the minimization of the deviation from the best-case scenario objective value (here: total project makespan), while solution robustness covers the minimization of schedule deviation between scenarios (Herroelen and Leus 2005 p. 291; Scholl 2001 pp. 99–102). Aim of this section is the identification of the most robust strategy $\Pi(Z)$ in all scenarios Z.

In deconstruction projects, the focus mostly lies on the compliance with time constraints regarding the project deadline C_{max} (Schultmann 1998 p. 123) due to tight time schedules of owners, clients or (general) contractors. Often, subsequent reuse of the land parcel or remaining building parts is planned for the time span immediately after the deconstruction project is completed. Thus, quality robustness with a reasonably good objective value under any likely scenario (Artigues et al. 2013) seems most appropriate in deconstruction projects.

Furthermore, in deconstruction projects often bulky and large resources such as long-front hydraulic excavators are needed that induce high transportation cost, organization effort and compliance to other projects' deadlines in the project portfolio. Thus, changes in deconstruction schedules are associated with additional setup time, potential project delay and cost to organize necessary resources. Therefore, on the one

[38] See section 3.2.4 for details on robustness criteria and their definition and section 3.2.3 on decision makers' preferences.

hand optimality-robust strategies Π seem appropriate to robustly plan deconstruction projects. On the other hand, a solution-robust (stable) schedule is also preferable from a time-based, a cost-based and also from an organizational point of view.

Here, quality robustness criteria is regarded to be the more important robustness criterion and deconstruction strategies Π^* with a lower total project makespan $C_{max}^{\Pi^*(Z)}$ over all scenarios Z are preferred. If two strategies have the same objective value in all scenarios both in the initial planning at time $t = 0$ and in later stages s $(t > 0)$ via induced local search (model part D, see section 4.5.3), the solution robustness criterion is additionally applied. Here applied robustness criteria are mean, variance and the standard deviation of project makespan as well as Laplace criterion (risk neutral). Risk averse criteria are the maxi-min-criterion[39] that considers the best strategy in the worst case scenario and the Savage-Niehans criterion that considers the regret (= minimal potential damage) in comparison to the risk neutral Laplace criterion. For comparison purposes, also the μ-σ-rule is applied with differing risk factors q with $q = -1$ (risk averse) and $q = 0$ (risk neutral) and risk taking maxi-max-criterion criterion is calculated and presented. These are the most common criteria to evaluate robustness and are sufficient[40] for the evaluation of robust deconstruction schedules.

In the application case of building deconstruction, rather conservative robustness criteria are applied for decision maker recommendations due to the fact that mainly small and medium size companies are acting in this field that are deciding in a rather risk averse way. Also, the mercantile prudence concept generally tends to pessimistic or risk-averse

[39] As the number of scenarios is finite, the minmax rules can be applied to generate strict quality robustness (Goerigk and Schöbel 2013).

[40] Criteria such as the fractile or aspiration criteria (Scholl 2001 p. 52) are not applicable as the examined scenarios do not have assigned probabilities. Other possible criteria such as the Hurwicz rule can be found e.g. in (Hazir et al. 2010). The hybrid Hurwicz criterion is not used as the risk preference factor λ is not known for deconstruction project managers and decision makers in the deconstruction field. However, the model can be easily complemented by this robustness criterion if needed.

preference (Spengler 1998 p. 72). Thus, the related conservatism in robust scheduling (Hazir et al. 2010 p. 634) in the sense of the preparedness for as many cases as possible seems adequate in this application case. In this case, a risk-neutral decision maker is assumed that identifies his ‘optimum’ strategies via absolute regret criterion where the strategy with the best performance in all scenarios z_k is preferred or where the regret of the deviation from the best objective value of each scenario is minimal. In particular, this approach aims at proactively finding a total optimality-
robust strategy $\Pi^*(z_k)$ where all absolute regrets (earliness and tardiness) of the deconstruction strategy Π is $AR(\Pi(z_k)) = 0$ for all scenarios $z_k \in Z$ and at the same time finding a solution that comprises the ‘most’ solution-robust strategy. If occurring, dominant strategies ($AR(\Pi(Z)) = 0$) that perform equally or better than other strategies under the same conditions (scenarios) are recommended to the decision maker. If there are no strategies Π with zero absolute regret, then strategy with the minimum average project makespan C_{max} over all scenarios is chosen. Result is a ranking of alternative deconstruction strategies Π according to their average absolute regret, with their mean objective value, μ-σ and μ-σ^2 of the objective value.

4.6 Model part D: Information updates and project changes[41]

In the context of operative deconstruction planning, single stage planning might be applied after building inspection with the collected building information, assumed potential risks and measured input parameters to provide the baseline deconstruction strategy. But during the course of most projects, unforeseeable events or new information (information updates) on activities durations, resource availability, or precedence constraints arise and changes in the project plan might be needed due to

[41] Parts of this section have been published previously in (Volk et al. 2015a; b).

external influences (Herroelen and Leus 2004 p. 1600). During deconstruction project execution, further information e.g. about building elements' volumes and existence or occurrences of hazardous materials might be generated through measurements, through dismantling of technical equipment or other building elements or through the removal of layers which might influence the subsequent activities. This might generate new information which might cause baseline schedule infeasibility, due to changed activity durations, changed mode or resource assignments or additional/omitting activities. Dynamic information updates are not realized in existing deconstruction project planning models yet (Schultmann 1998, 2003; Seemann 2003), but seem necessary in practice to cope with the unforeseen uncertainty occurring during project execution.

If a system or project under consideration has uncertain or incomplete future information, it is necessary to use a sequential decision making approach (Comes 2011) to repeat the planning at different time stages[42] and information levels (Scholl 2001; Scholl et al. 2003 p. 1). This data assimilation can include detailing of coarse initial information, falsification or verification of current assumptions, improved probability information or a final occurrence of certain events and thus a determination of (problematic) data (Scholl et al. 2003 p. 1) and can lead to improvements in model calculations e.g. by narrowing possible scenarios or reducing the number of activities to be scheduled. Scholl (2001) reports improved results due to the possibility of reaction during project execution (Scholl 2001 p. 140).

Accordingly, deconstruction projects should be planned in multi-stages. The multi-stage condition with step-by-step planning is desirable to depict different information levels during project execution where each stage is characterized by an information update. And, when decisions only depend on formation available at time t (that is, ξ_t) and not on later

[42] Stages are possible decision points in variable intervals, equidistant intervals or in increasing intervals over project time (Scholl 2001) (see also section 4.3.6).

observations at $t+1$ (ξ_{t+1}), the non-anticipativity condition is fulfilled (Shapiro et al. 2009), which is "the basic requirement in multi-stage models." (Fernandez et al. 1996; Heitsch et al. 2009; Rafiee et al. 2014 p. 2128). As in deconstruction projects information is incomplete and project structure is evolving during project execution, it is important to meet the non-anticipativity constraint. In this model, the non-anticipativity is fulfilled as scenario construction at time t is only based on information known at that time. Future potential project changes or potential information updates in $t+1$ are not previously considered in the scenario construction and decision making at time t.

To provide an overview on the dynamic model part D, Figure 4-14 exemplary shows the model steps over time. In the first stage ($s=0$) at time $t=0$, the project is scheduled based on the available information at that time (observation vector $\xi_{t=0}$ according to Rafiee et al. (2014)) including information on the building configuration (building element material, building element volume). Then, a robust decision based on scenario generation (model part A) and decision (model parts B and C) is made and the project begins. In this example, at time $t=6$, new information arises. Then, at this decision point (stage $s=1$), the observation vector changes to $\xi_{t=6}$ including now the new information at $t=6$. This can be the case, when a building element revealed to be of another building material (e.g. hazardous materials) or to have another volume than expected from site inspection. Then, with the new information $\xi_{t=6}$ at hand, it has to be evaluated if the robust baseline schedule is still feasible. If the schedule is still feasible, no project plan changes are necessary. If the project plan becomes infeasible, a different project plan has to be identified. In the example, the information update leads to a scenario generation and thus implies that the baseline schedule becomes infeasible by the new information at $t=6$. Then, based on the new scenarios $z_k(1{,}6)$ with the new information, a robust strategy Π is selected, a respective schedule $Sched(x_{1,6}, z_k)$ is generated and the project proceeds with this new schedule until the next information update arises (re-scheduling). In the example, at time $t = 10$ also an information update occurs, but it does not evoke a new scenario generation. This might be because of two reasons. Either, the prior 'baseline' schedule that was created in $s = 1$ $(t = 6)$ remained feasible. Or, the prior schedule became infeasible, but beneath the already found and evaluated strategies Π a feasible and 'near' strategy could be identified as the new 'baseline' strategy (local search).

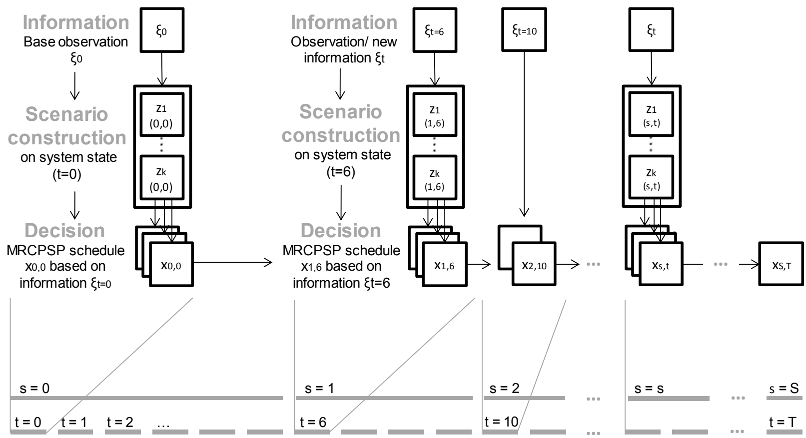

Figure 4-14: Exemplary functionality of dynamic scheduling during project makespan T with multiple stages s=0,…,S and new information ξ_t (observation)

The following sub sections define the type of information updates that might occur and their potential changes in project schedules (see section 4.6.1) that were already discussed in the short example in Figure 4-14. With certain information updates, there might be no need to change the strategy, but the activities take longer and the schedule is right-shifted (see Figure 4-15, left). In section 4.6.2, a local search procedure is described which is applied in several cases of information update and can be seen in the right part of Figure 4-15. If no alternative strategy can be found in the already evaluated and ranked set of strategies, then a re-scheduling is applied which is described in section 4.6.3 and leads to a new scenario construction and the identification of new strategies under the changed information and conditions.

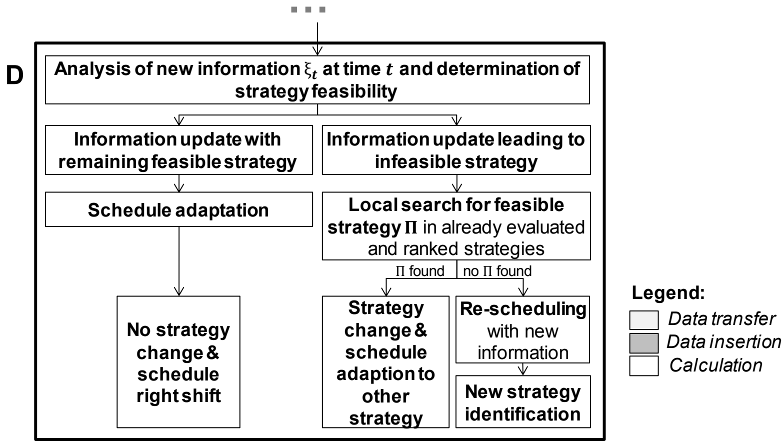

Figure 4-15: Overview on model part D

4.6.1 Definition of information updates and project strategy/schedule changes

Usually, the project planning uses apriori information. If during project execution information updates or changes occur, baseline schedules of the apriori planning process might become obsolete or infeasible during project execution.

Reasons for schedule infeasibility can be manifold. For example, a project can be interrupted, project activities can be prolonged, resource capacities can decline, etc. Depending on the time instant t of the information update and the type of information that was updated, effects on schedule or strategy feasibility are different. In every case, it has to be determined if the information update leads to schedule infeasibility. Generally, there are several possibilities to react in the case of baseline schedule infeasibility. These possibilities are often named reactive procedures of MRCPSP and include exact and heuristic (partial[43]) schedule repairing policies (Deblaere et al. 2011b), rescheduling of the remaining activities under the new information and conditions, mode switching[44] (Godinho and Branco 2012), increase of resource availability (Zhu et al. 2005), right-shifting of the baseline schedule or local search in already considered schedules.

Two basic concepts of value and structural information update can be differentiated (Comes 2011 p. 232). In this case, value information updates rather lead to right-shifting of the project schedule or to local searches for project strategies while structural information updates (with additional activities or with increased resources) rather lead to re-scheduling. To decide, whether value or structural update is applicable, the type of new information has to be determined. E.g. if additional activities are detected, a rescheduling is necessary and if only activity durations changed, a local search would be more successful.

Furthermore, in stages $s \geq 2$, project information has to be separated into realized activities $x_{jmst}^{\varphi} \in \varphi_{s,t}$ at stage s and remaining, planned or modifiable activities (decisions) $x_{jmst}^{\phi} \in \phi$ for future stages s+1,…,S_{ges}. In each project stage s, the realization matrix $\varphi_{s,t}$ saves the previously made and realized decision during project execution at time t and stage s. The observation matrix $\xi_{s,t}$ with building elements (rows) and material and volume information (columns) saves the real occurring building element material and volume, e.g. for later costing, evaluation, and experience values/databases. Here, project information updates are assumed to be registered and managed by a decision maker. However,

[43] Some parts of the schedule might still be executable or feasible despite a project or activity.

[44] According to Godinho and Branco (2012), a priority-list of the modes can be determined for each activity according to their expected activity duration and their expected cost to apply adaptive policies based on schedule infeasibility and information change (Godinho and Branco 2012 p. 555). However, they do not consider renewable resources and their uncertainties (Godinho and Branco 2012 p. 553).

also automatic information updates based on up-to-date monitoring data as proposed by (Bertsch 2008 p. 149) seems possible in future work. In the following, five information types are differentiated: (1) changed resource properties, (2) changed activity properties, (3) + (4) changed building element properties with and without additional activities and (5) further changed project parameters. And, depending on the type of information, several cases need to be covered that are explained in the following:

(1) Changed resource properties (availability): If resource availability (number of available resources over time) changes at $s > 0$, two cases can be differentiated. Either the resource availability increases or decreases. When the resource availability increases, the decision maker can stick to the baseline strategy or can select any other (feasible) strategy from the list of strategies. However, in this case, the additional resource is not considered. But, as the additional resource directly affects the solution space of MRCPSP (as it might lead to a shorter project makespan), a re-scheduling seems to be more adequate to include the new information. However, if the replanning effort should be kept low or the solution robustness be kept high, a local search is a reasonable possibility to select another strategy from the list. When resource availability decreased, the alternative strategies have to be tested if they do not exceed the new resource availability constraints. When the strategy did not schedule the decreased resource in question, the respective strategy can be selected. Otherwise, a re-scheduling is necessary. If the resource cost changed, this might also be a reason for a strategy change. However, as resource cost e.g. staff/hour or machine/hour is a quite well-known (deterministic) value, in this research contribution uncertain cost are not further considered in the robustness evaluation and in the dynamic information updates. However, in the selection of the recommended deconstruction strategy, average total project makespan and average total project cost are selection criteria.

(2) Changed activity properties: If the activity duration changed, the strategy remains the same although the schedule might (dramatically) change by right-shifting rule of all remaining, successor activities. And, if the updated activity prolongation is very high, the selection of another strategy might become more attractive as it might shift activities to other resources and will result in a lower project makespan. Thus, the strategy list with its project makespan and the robustness measures are recalculated with list scheduling heuristic. For that purpose, the project makespan and the robustness measures for all deconstruction strategies on the list are updated with the new information and feasibility (according to section 4.6.1). In this context, information on the already performed activities $x_{jmst}^{\varphi} \in \varphi_{s,t}$ and their resource usage is needed.

(3) Changed building element properties (without inducing additional activities): If building element properties changed (without inducing additional activities) another mode selection needs to be made for the affected activities to make the deconstruction strategy (or schedule) feasible again. Thus, only those strategies can be selected from the list in a local search, which provide another mode assignment for the respective activities. Then, similar to the procedure in (2) the schedules, project makespan and the robustness measures are recalculated for the remaining activities (decisions) $x_{jmst}^{\phi} \in \phi$.

(4) Changed building element properties (with inducing additional activities): Information on building element properties can change and the changes can result in additional activities that were not-anticipated or simulated in the scenario construction. For example, the detection of hazardous materials that need special treatment and protection measures or the necessity of rework might lead to additional or different activities. Then, again two cases can be differentiated. Either, the additional activity can be (easily) included

into the existing strategy, e.g. by grouping of the activities and thus prolonging already planned activities. Then, the procedure similar to (2) is applicable. Or, the additional activity cannot be easily included, e.g. due to new precedence constraints, then a re-scheduling with the remaining activities (decisions) $x_{jmst}^{\phi} \in \phi$ and the new information and conditions is more appropriate.

(5) Further changed project parameters: If further information updates lead to change of other project parameters, the related action (local search versus rescheduling) depends on the related effect on the strategy or schedule. Model parameters such as the density of materials, the duration coefficients (DC) or the standard dimensions of building elements (e.g. washbasins, toilets, width of window or door frames etc.), have an effect on the related building element properties and thus on the related deconstruction activity duration. Similar to (3), this would lead to a recalculation of the values in the strategy list. Other model parameters such as the suitability of modes to materials or to building elements for example have more profound effect on the solution space as it directly affects mode selection. Thus, in this case a re-scheduling is inevitable to include the new information adequately.

4.6.2 Local search of promising robust alternative strategies

Due to usually larger problem sizes of real deconstruction projects, a local search is proposed to quickly find another robust solution. If a baseline schedule that was created in $s = 0$ and $t = 0$ becomes infeasible due to an information update or change in project plan, a local search in the already identified and evaluated deconstruction strategies can be performed. If a 'quite robust' deconstruction strategy ('near' to the robust baseline deconstruction strategy) can be found that is feasible

under the new conditions, the baseline schedule is replaced by this strategy.
The local search is following the four types of information updates, feasibility (see section 4.6.1) and the mentioned selection criteria. It aims at finding a 'near' strategy that fulfills the new requirements after the information update or change in stage $s > 0$. A 'near' strategy in this sense is a strategy from the original list that is feasible under the new conditions and has a reasonably good objective value. Here, different values for 'nearness' of the quite robust strategy to the baseline strategy need to be defined by the decision maker. The found strategy already includes the robustness evaluation and allows the direct comparison of the original baseline strategy and other strategies based on their objective value and robustness criteria values.
If no adequate deconstruction strategies can be found in the evaluated strategy list that respect the information updates regarding precedence or resource usage, a re-scheduling of the remaining activities (decisions) $x_{jmst}^{\phi} \in \phi$ under the new conditions will take place (see section 4.6.1).
The advantage of the local search is that it is relatively quick compared to the rather slow and time-consuming updating of input data, project parameter update, scenario generation, and the re-scheduling with the new information. However, the information updates are numerous, different types occur conjointly or additional activities occur during the project execution. Then, the most appropriate alternative strategy from the list has to be carefully selected to fulfill all new information, conditions and constraints. If the number of information updates and their types are unmanageable, they can only be integrated via re-scheduling of the remaining activities (decisions) $x_{jmst}^{\phi} \in \phi$ under the new information and conditions although this might take some time.
This approach appears similar to contingent scheduling approaches (Herroelen and Leus 2004 p. 1612) that focus on grouping activities and enumerate different intra-group activity sequences. When a schedule disruption occurs, a switch from other sequences are proposed to avoid

losses in project performances. In contrary to these approaches, sequences (strategies) for the whole project are identified and the recommended strategy is selected by based on its quality robustness performance.

4.6.3 Scenario updates and rescheduling

If a re-scheduling (wait-and-see)[45] is needed, model input data is updated so that updated model parameters and all remaining activities x_{jmst}^{ϕ} are the new model input. From the remaining activities or rather their related building elements again scenarios $z_{k\prime}$ are created. If the information on the building elements' properties did not change and several activities are already completed, it can be interpreted as a scenario update. A scenario update is defined as the modification of a scenario according to a change of information (Comes 2011 p. 85).

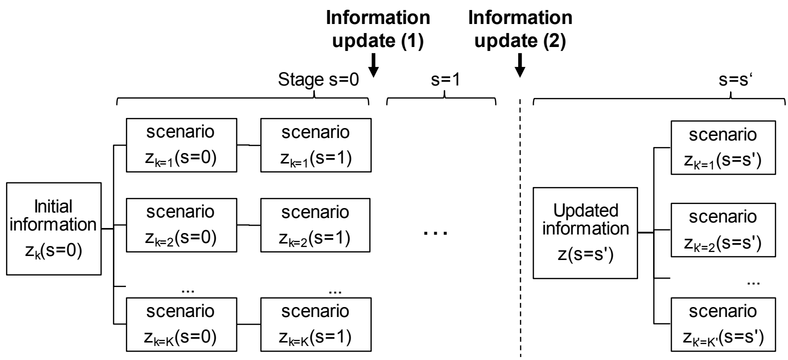

Figure 4-16: Exemplary scenario updating tree with three stages (decision points)

45 See section 3.2.5 for description of 'wait-and-see' approaches and multi-stage scheduling.

Figure 4-16 shows the creation of k scenarios at stage $s = 0$ based on the initial information (observation ξ) before project start ($t = 0$). Then, in stage $s > 0$, an information update (1) is shown where the original scenarios are updated (reduced) by the completed activities. This equals the local search for a still feasible and 'reasonable good' robust strategy. In stage $s = s'$ however, new scenarios are generated due to another information update (2). E.g. if the building element properties changed, the rescheduling includes the creation of new scenarios. In this case (2) the scenario update reduces the original scenarios by the already performed and completed project activities and adds, if necessary, new building elements to any new scenario $z_{k'}(s'), \forall k' \in K'$ (see Figure 4-16). Thus, it can be named a structural update according to (Comes 2011 p. 233).
During this iterative process, the problem size is reducing due to the increased number of completed activities and the reduced planning horizon. Thus, towards the end of the project re-scheduling the remaining problem becomes easier and faster.

At each stage, the information update ξ_{st} (project status) as the observation on still inherent building elements is updated. Re-scheduling is similar to initial scheduling based on ξ_{st} and the sets of remaining (previous and newly added) activities to be scheduled ϕ_{st} at the time t and at each stage s. Rescheduling describes the MRCPSP procedure (model part B) where a scheduling problem with the remaining activities $x_{jmst}^{\phi} \in \phi$ is created and solved per scenario (see section 4.4). Then, like in in the initial planning process, the resulting deconstruction project schedules are transformed into deconstruction strategies (see section 4.5.1), the strategies are applied and evaluated for all scenarios (see sections 4.5.2 and 4.5.3) and a new robust deconstruction strategy is chosen. To calculate the total project cost and duration, the set of already realized and completed activities, their realized mode assignments and activity durations are stored in φ_{st} for each activity j or activity set j' at the time t and at each stage s.

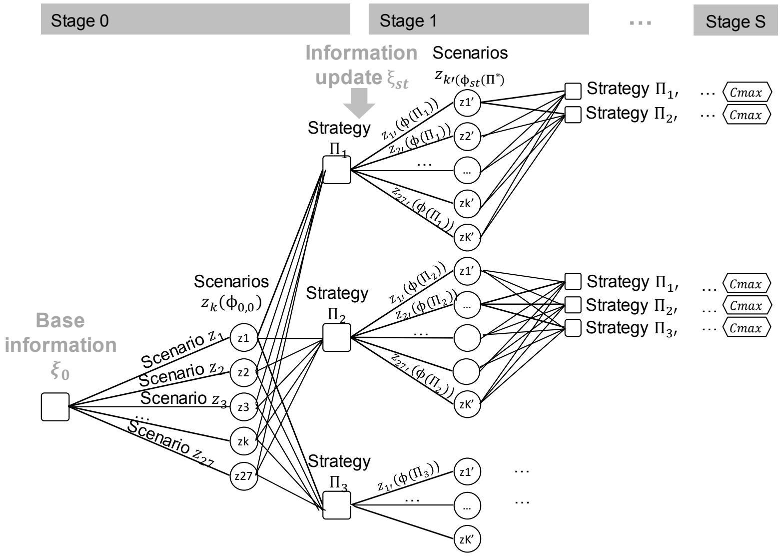

Figure 4-17: Ex post decision tree for multi-stage deconstruction projects with strategies (decision nodes) and scenarios (chance nodes) of the first and later stages

The presented model part D includes information updates at stages $s = 1, \ldots, S$ and fulfills the non-anticipativity constraint. Thus, the approach belongs to the multi-stage project planning approaches. Ex post, the process can also be seen as a decision tree (see Figure 4-17) where from the initial scenarios z_k strategies are generated and evaluated and the selection of the strategy Π^* can be modeled as a decision. In this case at stage $s = 0$, the scenarios z_k are constructed without any complete activity ($\phi_{0,0} = \{\}$) while in later stages the scenario construction depends on the previously selected strategy $\phi_{s-1,t}(\Pi^*(Z))$. Then, the planning process starts again in the next stage with the remaining activities $\phi_{s,t}(\Pi^*(Z))$ of the previously chosen strategy (decision). However, the stages and information updates as well as their effect on the project realization and the remaining activities can hardly be anticipated a priori and probabilities of occurrences are not known beforehand. Thus, here this is considered in a reactive way.

4.7 Summary, discussion and conclusion

Section 4 formulates the developed mathematical model that includes uncertainties into deconstruction project planning. This section provides a summary (section 4.7.1) of the model and a critical discussion (section 4.7.2) of the model structure and underlying general data. Case-specific data is described and discussed in chapter 5. Furthermore, conclusions are formulated and an outlook on potential model extensions and future research is given (section 4.7.3).

4.7.1 Summary

In chapter 4, requirements for deconstruction project planning were formulated for deconstruction project planning systems. Then, the formal model is developed and a model overview is given, followed by the detailed description of the single model parts A, B, C, and D. Part A includes a building inventorying logic based on imported sensor information, that is gathered during building site inspection. Then, occurring uncertainties in building auditing (building element-related) and deconstruction planning (activity-related) are systematically analyzed. Also, it describes a scenario construction based on the building inventory and inventorying parameter variations and uncertainties that can occur. Part B shows how deconstruction activities are derived from the different scenarios and their building inventories and schedules the activities in a multi-mode, time- and resource-constrained capacity project scheduling problem (MRCPSP). Based on the optimal solution per scenario, total project costs are calculated. Part C describes the transformation of deconstruction schedules into deconstruction strategies and their evaluation with respect to risk-averse robustness criteria. Part D details the potential processes during project execution, when new information on the project status, the building elements, the resource capacities and other project parameter arise. In this model part, a local search or a re-scheduling are proposed and described depending on the type of new information during project execution and their impact on remaining activities and project schedule.

The developed approach is a scenario-based, proactive-reactive (robust), multi-mode resource-constrained project scheduling (MRCPSP) approach that minimizes the total project makespan of deconstruction projects and that provides a robust baseline schedule that incorporates a certain degree of anticipation of potential variability. To proactively consider foreseeable uncertainties in building configurations, a scenario construction is implemented. And, the model is able to derive deconstruction activities from the building inventories and to group the activities to activity sets of common deconstruction works. Also, the activities follow the specific precedence relations of deconstruction projects. Furthermore, the activity derivation is easily extendable onto further downstream activities of sorting, crushing, loading, or transporting activities. The MRCPSP also was extended to locations that are modeled as renewable resources that are subject to further location-specific constraints where parallel works in the same locations are excluded. The MRCPSP is also considering multiple execution modes as alternative deconstruction activity techniques with different resource demands and resource capacities are met during the whole project makespan. The multi-mode modelling allows model users also to depict different abilities and productivity rates of staff and resources. This is modelled for the differentiation of staff qualification into machinery operators and normal workers, and it can easily be extended and applied to other resources. And, as staff or teams are working in different performance levels (production rate) that practitioners and experts estimate up to 30%, explicit differentiation of performance levels might also be considered in future work.

Also, to fulfill the requirement in deconstruction project planning and in advantage to stochastic scheduling, this approach provides a baseline schedule for the information of stakeholders and the allocation of resources. Furthermore, decision makers' rather risk-averse risk preferences in deconstruction contexts are considered in this approach in the selection of the robust deconstruction strategy. Changing information on variable time instants during the project execution is also integrated in the developed planning approach, as the scenario construction and the MRCPSP is applied in a multi-stage project planning process. This allows decision makers to change the original baseline schedule during project execution but at the same time provides decision making support regarding the schedule change. Furthermore, many model parameters can be easily adapted to decision makers' needs and experience values. For this reason, a graphical user interface and an import function from Microsoft Excel has been designed and implemented to facilitate model parameter adaptations by the user. And, the model is programmed in an object-oriented way that allow extension to other building types and transfer to other, similarly structured problems.

The presented predictive-reactive (robust) scheduling approach is based on previous works of MRCPSP under uncertainty. The difference to known approaches is the strong relation to the presented application case in deconstruction projects, as well as the extension by a scenario construction to get more suitable activity durations, the consideration of locations in MRCPSP and integration of the optimality-robustness criterion. Deficiencies of existing static, deterministic deconstruction scheduling approaches are overcome with this approach such as their inabilities to consider uncertainties and information updates that arise after a scheduling decision has been made and that might induce other decisions (schedules) in subsequent project stages. The proposed problem formulation and solution follows a total planning approach (all activities are planned at once), however due to potential future information updates only the short-term activities can be seen as compulsory, whereas the later planned activities can rather be considered provisional and can be changed by later incoming information (similar to rolling wave but without regular planning intervals and plan overlaps). As according to the model deconstruction projects are executed until an information update arises and might change the project schedule, the reactive model element can be seen as a wait-and-see approach. Also, the proposed method belongs to the class of flexible project planning (according to the definition of (Scholl et al. 2003 p. 12)), as it generates in each stage baseline plans for 27 scenarios that might serve as alternative plans in the case of the realization of another scenario. But through the selection of strategies (plans) it also belongs to the class of robust planning. Although risks in deconstruction projects can often hardly be quantified, the proposed approach offers a method to calculate potential impacts of several, main uncertainties (causes) in deconstruction projects and thus to quantify their risk (impact on project time and cost). The impact of the risk in each scenario is calculated in model part B and the approach proposes a deconstruction strategy with minimum risk impact on the project execution.

The main advantages of the presented (individual, 'micro') building-related approach lies in the high level of detail and thus expected realistic model results. Also the model allows a project scheduling (optimization) under consideration of uncertainty at all which had not been possible before. Also, the developed model enables decision-makers in deconstruction contexts like operators, planning engineers, architects and experts to robustly plan the resource allocation in deconstruction projects over the course of a deconstruction project. This approach provides decision makers with an improved planning information base for building inventorying, project planning and controlling (re-planning) (which is crucial in time (or cost) controlled industries like the (de-) construction industry) and has an appropriate compromise between planning effort and planning quality. Further benefits are the consideration of information updates, robustness and risks as well as hazardous materials into the planning with first priority in precedence relations (according to legal obligations). Otherwise, deconstruction project scheduling is done manually which will not necessarily provide the optimum schedule or consider uncertainties and risks. Furthermore, it allows a model user to select deconstruction strategies according to their risk preferences and to modify model parameters.

4.7.2 Critical appraisal and discussion of the developed model

As any other approach, also this approach has its advantages and shortcomings. Main model limitations, system boundaries, and shortcomings are described and discussed here following the order of the model parts (A), (B), (C) and (D). Also, potential model extensions and potential other approaches are sketched and shortly discussed.

The applied parameters in building inventorying, that cannot yet be captured by sensors (such as building element thicknesses, piping and wiring diameters, reinforcement factors etc.), are based on German standards. Buildings subject to deconstruction projects might not be built according to these standards and the applied parameters might be further improved by experience data or expert information. And, due to the case study data set, a roof inventorying logic was not implemented yet, but might be based on the detected ground floor area of the building and user information on the roof pitch, as literature and standards provide thumb-rule values to quantify roof covering and roof construction volumes (see section 4.3.2). Furthermore, load-bearing and non-load-bearing walls cannot be differentiated in the model yet. This results in potential deviations in building inventories due to varying element thicknesses or reinforcement calculations. However, the project activity precedence relations are not affected by different wall types, because it is assumed that all walls of one level are deconstruction jointly at the same time. Compared to existing approaches like (Akbarnezhad et al.

2014), the model is not based on a preexisting building (information) model but relies on processed sensor data. However, the model input data (sensor data set and potential building element parameters) might also include uncertainties and could not reflect the real building and spatial measurements of the building and building elements in question. Although (Akbarnezhad et al. 2014) considers scenarios and sensitivity analyses in his deterministic waste quantification tool, the level of detail is quite low and it does neither allow robust scheduling nor decision support.

Usually, scenarios are represented by decision or scenario trees where frequencies or probabilities are assigned to scenarios according to the stochastic properties of their baseline variables to allow simulation. "The possible variations of a material property are modelled using a set of probabilized variable settings" (Aissi and Roy 2010 p. 96). For several building types, a probability of their occurrence could possibly be derived from their frequency in total building stock (e.g. for Germany in (IWU 2012a), for Europe: (Enerdata 2015), see section 2.1.1). However, probabilities on inherent building elements and materials are not available. If scenario probabilities would be known, a simulation would be preferable to an enumeration of possible scenarios. However, in the application case of building deconstruction scenario probabilities are not known because stochastic distributions of baseline variables (building element properties) are not known. An assumption on equally distributed scenarios with $p(z_k) = 1/K$ is possible with scenario z_k and with the total number of scenarios K due to a insufficient reason for assuming another distribution (Scholl 2001 p. 55). This would allow a simulation on random scenario samples that are drawn from the total scenario set. However, this kind of simulation has limited meaningfulness and interpretability as it leads only to a seemingly better basis of information, while it might not describe reality adequately anymore (Scholl 2001 p. 55). The presented approach is not considering all combinatorically possible scenarios. The main disadvantage of a multitude of scenarios is the consequently high computing effort. As shown in section 4.3, the number of scenarios would be very high and the calculation of optimum schedules for all scenarios would not be possible in usual decision time frames. The proposed approach instead includes the best and the worst case scenario which give decision makers the idea of the range of potential outcomes. However, real scenarios might be not equally distributed between the extreme scenarios (Scholl 2001 p. 137) and a prediction on the interval or the statistical confidence level is not possible (Girmscheid and Busch 2014 p. 145). Consequently, a reduced number of scenarios was constructed, but this might not depict reality and might be extended by further scenarios, e.g. with smaller or larger uniform volume variation (+/-5%, +/- 20%), other influence parameters (e.g. external uncertainties) or uncertain resource availability. But as discussed before, a proactive consideration of uncertain resource availability would result in a tremendous scenario increase which would not be manageable.

Here, only variation and foreseeable events and related impacts on activity prolongation or different resource demand in the proactive scenario construction (part A) and reactive project management (part D) is covered by the approach. Unforeseeable or unknown events such as schedule disruptions are not included proactively as their occurrence and effects are hardly quantifiable. In the scheduling context, Aytug et al. describe a taxonomy for execution uncertainties (Aytug et al. 2005 pp. 91–94). However, as execution uncertainties are manifold and often unforeseeable, they are not included proactively. Instead, they are included on a reactive 'wait-and-see' basis in the reactive model part D (section 4.6). Here, a decision makers' reaction is possible after an unforeseeable event e.g. if resources become unavailable or if additional activities have to be included into project schedule. Also, not all foreseeable uncertainties or other types of uncertainties might have been included into the approach. So, resource availability or additional activities for example might also be proactively integrated into scenario construction via additional scenarios where most inflexible resources have varying availabilities or where most probable additional activities are included. However, this would considerably increase the number of

scenarios. As discussed before, the number of scenarios is intentionally kept quite low to ensure solvability. However, if computational performance of computers is further increasing, the number of scenarios might also be increased.
Furthermore, other project-related uncertainties and risks beyond the building information related uncertainties are not analyzed yet nor are they identified, listed and assessed in a Risk Breakdown Structure (RBS). But, they might be subject to future research regarding decision making support during project execution. Statements on expected risk cost of a deconstruction activity or project or their range or statistical certainty are not possible (Girmscheid and Busch 2014 p. 145) due to unknown probabilities of occurrences of risks. And, it is not possible to quantify the 'shares' of included and neglected uncertainty, as unforeseeable uncertainty and chaos cannot be quantified.

Simultaneous planning in a total model considers reciprocal interdependencies between decision sub-problems but, it is not applicable in long-term planning (Scholl 2001 p. 21) and might not be useful when incomplete information prevails. As there is no clearly best method for managing arbitrary multi-project organization (Herroelen and Leus 2004 p. 1613) under uncertainty it depends on the project context which methods are best suitable. Deconstruction projects can be seen as rather independent onsite projects that are often performed with a certain amount of resources, although shared resources like staff or hydraulic excavators and also single subcontractors (like decontaminators) occur. Another affecting influence on project independence are milestones or due dates which in deconstruction projects mostly apply in the project completion (project deadline). Also, the projects can have a moderate to high variability which qualifies them according to (Herroelen and Leus 2004 p. 1614f.) i.e. for predictive-reactive approaches considering robustness. And, this approach is applicable in a single-project manner (Herroelen and Leus 2004 p. 1616). However, the determination of the optimal degree of deconstruction or the tradeoff between minimal project makespan and minimal project cost cannot be answered by the model.

The proposed approach tries to depict real deconstruction situations as realistically as possible not only to allow practical decision support but also to allow multiple applications of the model and future developments and extensions e.g. in retrofitting. This induces an increased model size which comes along with increased expected computing times. To narrow both model size and computational effort, a tradeoff between representation of real processes and modeling/solving complexity[46] has to be found, e.g. with respect to simplifications of building elements materials (level of detail), activity aggregation to deconstruction groups or the definition of time slices. The Level of Detail (LoD) of activity modes, resource, building elements and their properties is important in the model as it implicitly influences model results and both represented and not represented uncertainties. The chosen granularity is able to describe the key building elements and activities in building deconstruction, but can be further detailed in future, e.g. the model is limited to certain types of TEQ yet as elevators or air conditioning supply lines are not calculated by the model yet. And, when the data quality and reliability is low on a detailed level, aggregation might increase the prognosis quality (Scholl et al. 2003 p. 12). For small sample projects exact optimal solutions might be computed, but it might be impossible to optimize large projects with numerous activities. Thus, in the model, the difficulty is to find an adequate deconstruction activity grouping. Because, for smaller deconstruction projects no grouping might be necessary, while for larger projects the activity grouping is essential to keep the problem solvable. Then, alternative approaches such as another activity grouping, rough and detailed planning or rolling wave might be applied to just consider activities in the near future. Also, the solution procedure might be changed to heuristic procedures to ensure solvability. It was aimed that this selection of the level of aggregation (level of detail) should be

[46] For considerations on model complexity and computational effort see section 4.4.4.

performed in an automated way. However, it was not possible to identify a routine to automate this step. Thus, this model parameter 'level of aggregation' is predefined by the model, but it has to be redefined by the user for each project and strongly depends on the project size.

One major limitation of the proposed model is that no preemptive activities are allowed so that no change of modes during activity performance is possible and activity disruptions are not modelled. Also, unplanned schedule disruptions and activity preemptions are not explicitly anticipated in the model and in the baseline schedules. In classical, stochastic RCPSP, preemptions are assumed to occur stochastically e.g. in production or machine scheduling due to machine breakdowns, to weather or other unexpected events. Preemption of activities can be modeled by splitting one activity into two activities with the same or differing resource demands and two sequential starting points before and after the preemption interval (interruption). In stochastic RCPSP, the time instant of unexpected preemption is uncertain as well as the longitude of the interruption and can only be modeled if their probabilities of occurrences are known or can be assumed. But, as deconstruction projects have a unique character, these probabilities are not known and can hardly be assumed. Information is incomplete in deconstruction projects and project structure might be changing during project execution. Thus, it is important to consider preemption of activities, if unexpected events or findings occur. But, information on activity preemptions can hardly be anticipated. And, although splitting of activities might lead to makespan reductions, for reasons of set-up times and set-up costs for each activity, the assumption of preemptive activities is avoided in practice and more realistic (Schultmann 1998 p. 115f.). As in his model decision points (stages) are applied, the model reactively allows the preemption of activities. However, due to the scenario-based deconstruction strategy selection a certain degree of activity prolongation e.g. due to activity disruption or delay is considered. As information is incomplete in deconstruction projects and project structure might change during project execution, it could be important to implement a flexible project structure (Hartmann and Briskorn 2010 p. 5; Neumann 1999), if unexpected events or findings occur. In the proposed model, structural project changes are considered by the reactive model part D.

Due to the often lacking data regarding older buildings designated to deconstruction and available information only from small samples, non-parametric estimation methods or experience values are applied to depict activity durations and cost. “However, even when using multiple modes, one major problem in modeling deconstruction processes is the fact that data is not always available to put mathematical models at work. In particular, the duration of deconstruction tasks involving human labor as well as sophisticated technologies is seldom precisely known due to the uniqueness and uncertainties of construction tasks.” (Schultmann 2003). Theoretically, distribution parameters of activities’ durations could be derived and used for stochastic scheduling. In the case of deconstruction projects, beta distribution might be adequate (Chen and Li 2006; Nickel et al. 2014 p. 166) to represent deconstruction activity duration, because it has upper and lower bounds and right-skewedness. However, distribution parameters p, q, α and β are not known for deconstruction activity durations and have to be estimated from the duration distribution of activities over all generated scenarios or from previous project documentations. As project documentation in this field is not comprehensive, this possibility is not further considered here. And as in real-life project execution, data may not correspond to the initially predicted values (Aissi and Roy 2010 p. 94), information updates and data changed are considered reactively as their prediction is often not possible. Currently, also set-up times and set-up cost are not considered here and might lead to different optimal schedules and strategies. However, the model output provides the decision maker with a ranking of several deconstruction strategies where the decision maker can choose the most suitable for him, both regarding the resource assignment and his risk preference.

Scheduled activities focus on deconstruction preparation and deconstruction activities. Removal of contaminations and hazardous materials

is only included, if they are existent in the scenarios. Site clearance activities are not considered, as it is a very high effort necessary to model and list all inherent furniture and mobile waste. Crushing, sorting and loading activities are also not considered yet, but can easily be included into the approach. In the current model, each building element in the inventory generates a single deconstruction activity. This could be easily extended to the generation of several activities from a single building element (e.g. also of other types of sorting, crushing, loading or transporting activities, with productivity values of (Seemann 2003 p. 54)) that need to be performed after the building element is deconstructed.
Also, several technical constraints are not yet implemented in the model due to model size and complexity, such as maximum height or some specific deconstruction techniques (hydraulic excavator with long front outrigger). As rather low-rise buildings are considered here with five or six stories, the limitation of applied resources to a maximum height is not very influential on model results, because e.g. hydraulic excavators without/with long front outrigger reach up to 15m/35m (see DBU project report II, Table 8, sources: ABW (2012), Lippok und Korth (2007), Toppel (2008)). And, additional modes can easily be integrated into the model by extension of the related Microsoft Excel table by the mode information. Moreover, maximum building element thickness is not considered separately to restrict technically impossible building element and mode combinations. But, in the currently implemented assignment of building elements to activities and activity modes the adequacy of the technique for the building element in question is already considered. This might lead to unrealistic or practically unfeasible model results (see DBU project report II, Table 9, sources: Lippok und Korth (2007)). Also, preventive or protection measures (activities) are not considered in the project planning yet, but can be integrated without further effort. Furthermore, the deconstruction processes in a project are modelled from the economic or operational point of view. Thus, technical aspects might be neglected or disregarded, such as the exact representation of element connections and respective effort (time/cost) to lose/solve the

connections. To explicitly model production rates, efficacy and skills of staff or teams, either each worker or team has to be modeled separately as a renewable resource with their qualifications and durations coefficients. However, as this would increase the problem significantly, here only a differentiation of machine operators' and normal workers' skills and cost is modeled. Furthermore, material cost and consumables (diesel, gas, explosives) are not considered yet in the deconstruction project cost calculation, but can easily be integrated if respective data is available. And, in the scheduling model, containers, container spaces (locations) and container capacities (filling level [%], solid and bulk densities [t/m³] (Lippok and Korth 2007 p. 124, Table 2.10), pickup and replacement scheduling) are not considered yet, but can easily be modeled as a renewable resource in future model extensions.

Also resources could be further differentiated into different sizes, capacities or performance classes. For example, hydraulic excavators could be further differentiated into small (25-30 t), medium (45-65 t) and large (85-100 t) excavators with differing attachments, cost and space requirements. In the model, currently a hydraulic excavator with 42 t and 220 kW is considered. Furthermore, a wheel loader could additionally be considered, when the model is extended to loading and transporting activities.

Also, due to the structural information deficit, the regional recycling planning is difficult to automate and include in the model as long as local or regional construction sites with recycling material demand are not known.

Here, the minimization of project makespan is modeled. However, several other objective functions with respect to deconstruction projects are possible. In section 3.2.5 a general overview on potential objectives of the resource-constrained project scheduling problem is given (RCPSP). In deconstruction projects, the adherence to time limits (deadlines) or the minimization of project makespan often is the main objective. Almost as important is the minimization of project cost. In literature, either minimization of makespan under budget constraints or minimization of cost under time constraints is modelled (Schultmann 1998 p. 123ff.). Following the discussion on the difficult quantification of effects of decisions on project cost in (Schultmann 1998 p. 123ff.), here makespan minimization under resource constraints (incl. budget) is modeled. In deconstruction management practice, minimizing the makespan under multiple modes is by far the most important objective (Schultmann 2003). Other modeling approaches might include the single objective of resource levelling (Afshar-Nadjafi et al. 2013) leading to equally busy resources, minimization of cost or maximization of profit (NPV) (Hartmann and Briskorn 2010; Kellenbrink and Helber 2013), maximum credibility (Xianggang and Wei 2010), risk/uncertainty minimization of expected objective values, or the minimization of earliness or tardiness of activities or project completion. Or, earliness or tardiness can be explicitly considered in the objective function according to expected contractual penalties, due dates or other robustness measures e.g. discussed in (Chtourou and Haouari 2008 p. 185; Schultmann 1998 pp. 123–127). Moreover, a bi-objective minimization problem considering both main planning aspects (time-cost, time-resource, time-cost-quality, time-robustness) simultaneously is named tradeoff problem and often considered in OR literature (see section 3.2.5). Bi- or multi-objective RCPSP can be formulated, but often do not lead to ideal solutions with optimal solutions of each objective (Schultmann 1998 p. 129f.). Thus, the problem of weighting the single objectives against each other remains[47].

As in this model, exact solutions procedures are applied, the problem size of larger data samples or application cases might exceed the computational power or the available planning time. Then, heuristics can be applied to solve the MRCPSP. However, this might lead to worse results as heuristics do not provide optimal solutions. But, even with non-

[47] See Schultmann (1998) for an extensive discussion on time, cost or resource related objectives in deconstruction projects and their explicit mathematical formulation (Schultmann 1998 p. 122ff, constraints 4.29 and 4.30).

optimal MRCPSP schedules the proposed methods are applicable, although the model results would have to be carefully evaluated before use.

As a result of the robustness evaluation, the model recommends the decision maker 'only' a robust good strategy in all scenarios instead of a best practice (optimum) over all scenarios. And, execution cost and the completion time are two criteria which should be taken into account when choosing a robust schedule (Aissi and Roy 2010 p. 94). Currently, it is assumed that in the robustness evaluation (model part C) a total optimality-robust deconstruction strategy can be identified. However, when no total optimality-robust strategy is identified or strategies have equal optimality-robustness criteria values, also considerations on (partial) solution-robust strategies are integrated. The comparison of sub-schedules and sub-strategies with the same resource assignment but with different sequences of activities might lead to the most promising strategy. In the robustness evaluation, several risk-taking, risk-neutral and risk-averse robustness measures are applied. However, other robustness measures or preferences might better fit decision makers preference (e.g. others can be found in (Chtourou and Haouari 2008 p. 186) such as Bayes rule (expectation criterion), variance rule, expectation-variance-rule, fractal rule or aspiration rule (Scholl 2001 pp. 51–53). Risk preferences with minimum α-aspiration level to the objective value, which is likely not be undercut by the schedule in all and especially in worst case scenarios (Scholl 2001 p. 100f.), or downside risks which represent the amount the objective value that falls under a specific target (Birge and Louveaux 2011 p. 68) could be considered.
The schedule adaptation of local search proposed in model part D as a reaction to schedule infeasibility might not necessarily lead to the best robust schedule that would have been identified by a re-scheduling for the subsequent stage. However, it might provide the decision maker with a reasonably good solution in a shorter time and with a lower effort. Furthermore, potential schedule feasibilities could be dynamically

included in the model. But, this might lead to problems in model solvability, as already small problem instances are hardly solvable (Elmaghraby 2005).

Although this approach tries to identify, integrate and quantify uncertainties in the deconstruction process, it is still a constricted and simplified effigy of reality and the decision making situations. Thus, due to the mentioned constrictions and simplifications, consideration of the results and recommendations of the model have to be interpreted with these limitations in mind. Furthermore, the quality of model results strongly depends on the quality of the input data, experts' knowledge and experience data that is provided. But, as users and decision makers of the deconstruction industry will only use the model for planning support if they would understand the model functionality, the chosen scenario-based approach is easy understandable for practitioners. Otherwise, if the applied method is too complicated and model results would not seem reasonable at first glance, they would not adapt the system at all. And, the combination of proactive and reactive model elements is improving flexibility and robustness of project planning (Kao et al. 2006) and management.

4.7.3 Conclusion and outlook

In this subsection, a conclusion on the developed model functionalities and an outlook on further model extensions and future research beyond the developed model is given.

In building deconstruction, the consideration of uncertainties is crucial for project planning, scheduling and management. However, the literature review in chapter 3 showed that in this application case most approaches insufficiently apply project scheduling methods under resource constraints and uncertainty. A number of possible alternative approaches were described, analyzed and not selected and implemented in this approach due to several reasons and their applicability in deconstruction projects was discussed in section 3.3.

The here developed model tries to fulfill the requirements of deconstruction project planning and decision making support under uncertainty and therefore to close some of the before-mentioned research gaps. It allows the inclusion of uncertain data, as well as experience values and expert estimations in the project scheduling based on scenarios. Also, when new information arises, the current baseline schedule can be changed if necessary. However, if a ‘similar’ strategy is also feasible with fewer projects schedule changes (of activity sequences or resource assignments), this strategy is chosen. The model results show that the consideration of uncertainties in different building configurations and activity durations via scenarios has an impact on project scheduling, resource management and decision making in deconstruction projects. Furthermore, the consideration of robustness criteria and decision makers’ risk preferences leads to other preferred strategies and schedules than in the deterministic case that is considered usually. And, based on the generated scenarios, deconstruction project risks inherent in the building can be quantified by the model and be taken into project scheduling and costing considerations. As the model also considers locations into project planning, it secures that activities are not planned at the same time and location, so that staff safety and logistic aspects are respected. Furthermore, it shows the implementation of varying staff competencies (multi-skill) or productivity of resources.
Thus, the developed deconstruction planning model implements a new approach that can support decision makers in robust deconstruction project planning. The following chapter 5 shows the exemplary application of the deconstruction project planning model in a part of a larger hospital deconstruction project site in the northern part of Germany.

Future work might be concentrated on the further model extensions of the approach with respect to several different aspects:
Reactive or dynamic scheduling (e.g. schedule repair or rolling horizon) aspects could be extended to unexpected or unforeseen uncertainties and events. Dynamic scheduling seems promising by generating a deci-

sion matrix with an optimum decision sequence vector (schedule) for each stage. However, for this method activity duration distributions are necessary. But, in larger projects such as the deconstruction of nuclear facilities the problem might not be solvable due to high computational effort that is necessary even for very small problems (Elmaghraby 2005 p. 313). And, a reduced planning horizon of rolling horizon method might improve computation time especially if the project size and project makespan is high e.g. as in deconstruction/ dismantling of nuclear power plants or other infrastructure. However, the planning gap is problem specific and usually increasing with project advance/progress (Scholl 2001 p. 144). And, the length of the planning horizon and the objective at the end of each planning horizon are not easy to determine, and the integration of irregular (between decision points) information updates and the increased higher planning nervousness have to be discussed (Scholl 2001 p. 140).

In the proposed model, project costs are calculated via [EUR/h] including repair, interest rate and the monthly availability of the resource resulting on the resource assignments of the optimum project schedules. Other non-renewable resources are not considered yet. In deconstruction, main objective next to adherence to time limit is the compliance of budget. Thus, the model could be extended by non-renewable resources, e.g. to include a project budget constraint or a time-resource-cost tradeoff. The following potential formulation would include a mode-dependent resource demand q_{jm}^{n} of non-renewable resource n that does not exceed the available resource capacity Q_n for each scheduled activity j in each scheduling period t (budget) for the whole project:

$$\sum_{j=1}^{J} \sum_{m=1}^{M_j} \boldsymbol{q_{jm}^{n}} \sum_{\tau=EF_j}^{LF_j} \boldsymbol{x_{jms\tau}^{k}} \leq \boldsymbol{Q_n}, \quad \boldsymbol{n} \in \boldsymbol{N} \tag{4.60}$$

With the already calculated [EUR/h] information q_{jm}^{n}, the budget constraint could be easily implemented. However, costs are less important in deconstruction scheduling of buildings as long as the available budget is not exceeded. Here, scheduling is done with the assumption of sufficient budget available (Schultmann 1998; Zimmermann et al. 2006 p. 50). Also, an extension on continuous or cumulative resources e.g. energy, money or container capacity would increase the realism of the modeling of a deconstruction project (Schultmann 1998 p. 120f.). But, as the problem size is already quite large, renewable resource and also continuous and cumulative resources[48] such as stocks, container capacity or material storage onsite modelled by (Bartels 2009; Schultmann 1998) were not implemented to not further increase problem size and hamper problem solvability by out-of-memory errors. In future research, this might be integrated in this model e.g. via aspiration levels that have to be fulfilled to satisfy project budget or storage space.

Also, in the proposed approach, a weighting w_j of activities, resources or scenarios (reflecting priority, preference or cost) could be integrated that might also be variable during project execution. In future work, activity durations might be generated by stochastic β-distributions of activity durations that use potential building configurations and experience values of time factors of past deconstruction projects. Also, an activity buffering with idle resource capacities to secure deadlines as proposed by (Schultmann 1998 p. 121f.) could be implemented in the model as this was also found to be helpful in the creation of robust schedules (Hazir et al. 2010 p. 641). Also, the insertion of redundant resources and buffer times for activities on the critical path or which are expected to be vulnerable could be promising (Herroelen and Leus 2005; Van de Vonder et al. 2005). Future research of typical disruption schemes of activities and resource availability as in (Chtourou and Haouari 2008 p. 193) might be interesting. Furthermore, the model might be extended by an automated determination of working zones (locations) beyond rooms and stories that might better support deconstruction project planning or

[48] A multi-mode case of machine scheduling with cumulative resources can be found in (Trautmann 2001).

logistics. Also, additional information on the buildings' year of construction, on (expected building) element lifetimes, on renovation cycles or on LCA information (e.g. on materials' and compounds' qualities, resource outputs, material recyclability, or best recycling path) could be included into the scenario construction. Also, further project planning objectives could be integrated into the model, e.g. the ecological load/damage could be minimized in the project planning, e.g. as done by (Schultmann and Sunke 2007a). To keep up to actual (secondary) raw material prices and recycling and disposal prices and capacities, an interface to local or regional mass flow models or related recycling networks would be promising for the practical application of the model. And, to further improve decision making in deconstruction contexts, an extension to a robust multi-project scheduling approach as well as related project portfolio analyses seem necessary and promising to describe assignments of shared resources in different project sites.

Future research beyond the extension of the developed model might include the consideration of flexible project structure (with mandatory and optional activities, GAN/GERT) and to understand the effect of a variable degree of deconstruction. However, flexible project networks can hardly be solved in finite time yet. Also, a comprehensive risk management might be developed to further support decision makers beyond the project planning including a structured risk identification, possible risk interventions and measures and their controlling.

Furthermore, 'technical' improvements are also possible such as the implementation of an IFC or CoBie interface to building information models (BIM) to ensure interoperability with current and future architectural software and building documentation. Also, a graphical representation of the building-inherent and detected technical equipment and reconstructed wiring and piping could be realized to better support deconstruction project planning and decision makers. And, 'machine' learning by updating model parameters and databases on duration coefficients, material densities, standard element dimensions would be very helpful to improve model results. Especially, when supported by the further development of optical sensor data, the future research could further include project controlling by automated building auditing and information update of project status. And, future research might be promising transferring the approach to similarly structured problems, such as construction projects, retrofitting projects, dismantling projects of other building types, infrastructures or industrial facilities such as nuclear power plants or to dismantling and recycling of discarded transportation means or other complex products.

5 Application of the developed deconstruction project scheduling and decision support model

In this chapter, exemplary case studies are presented to demonstrate the developed deconstruction planning and decision support model. In the following, two case studies are presented that were used during model development and that show the exemplary model application and model results. First, the case study data sets and the main project-specific model parameters and their sources are described. Then, following the model structure, the inventorying and the scenario construction of each case is described (part A) and the MRCPSP scheduling optimization results are shown (part B). This is followed by the transformation of the optimal schedules in deconstruction strategies and their evaluation and ranking according to risk-averse robustness criteria (part C). The information updates of the reactive model part D are only occurring during project execution, but are also exemplary applied in case study 1. Therefore, based on assumed potential information updates and their impact on the baseline schedule, strategy change or rescheduling are discussed. Then, a verification and sensitivity analysis is provided in both case studies to examine the model results' plausibility and variability to different model input data and parameters.

5.1 Case study 1: Four-room apartment (residential building)

This section describes the exemplary model application for the deconstruction project planning of a fictive four-room apartment. The apartment is assumed to belong to the construction type II (according to Figure 2-5) that consists of a solid building construction with masonry walls and timber slabs. Section 5.1.1 describes the whole data set of case study 1 that is used for the deconstruction project planning and the model application. Section 5.1.2 shows the inventory results of the model and the scenario construction based on the building inventory. Section 5.1.3 provides the reader with the scheduling results for case study 1. Section 5.1.4 describes the model results for the robustness evaluation of the generated deconstruction strategies in this case study. Section 5.1.5 shows exemplary information updates and the effects on previously selected deconstruction strategies and on the later decision making during project execution. Finally, section 5.1.6 concludes with verification and sensitivity analyses of the generated model results.

5.1.1 Description of the building and used data sets

In the deconstruction planning model, several project specific and general data sets are applied to calculate building inventory, building element surfaces, volumes and masses as well as durations and cost of deconstruction activities. Necessary data for building inventorying and planning deconstruction projects are time, cost and quality information on the building and its elements. Sources of project specific data are onsite measurements (via CSV/OBJ interface) and user inputs. Sources of general building and building element data are standards (DIN, ISO), literature and expert estimations. This subsection gives an overview on the applied data sets in this case study.
Case study 1 constitutes an exemplary four-room apartment that is sketched as a 3D model in Figure 5-1 and its floorplan can be seen in Figure 5-2. The apartment consists of 49 building elements (see Table 7-3) based on a data set of 35 faces (=facial building elements) and 154 vertices (=vertex or compact building elements) in the CSV and OBJ interface files (see Table 7-4 and Table 5-1). Figure 5-1 and Figure 5-2 show some building element ID numbers that belong to the CSV/OBJ dataset (see Table 7-3).

Table 5-2 aggregates the number of detected faces and vertices in the CSV/OBJ data as well as the inherent building elements. In the deconstruction planning model, main building elements are foundations, floors, slabs and walls, with their coverings as well as doors and windows. Smaller elements and technical equipment can include coverings/coatings, insulation, appliances, equipment and piping of water, waste water, power, air conditioning, heating and elevation[1]. In this small case study, the focus lies on the main building elements and the electrical equipment.

In case study 1, data from the CSV/OBJ interface is imported (see exemplary data in Table 7-3, Table 7-4, (Appendix III) and Table 5-1) and building element surfaces, volumes and masses are calculated for the four-room apartment to create a building element and material inventory according to section 4.3.2 (see section 5.1.2). Further necessary information such as the room or building element height is either derived from the data set or based on standards such as the allowed zones of electrical wiring. For example, the standard wiring zones might allow conduit in a lower installation zone, but in the case study there might be a door forbidding the conduit of the electrical wire in the lower installation zone.

[1] A structured overview on building elements can be found in DIN 276-1:2008-12.

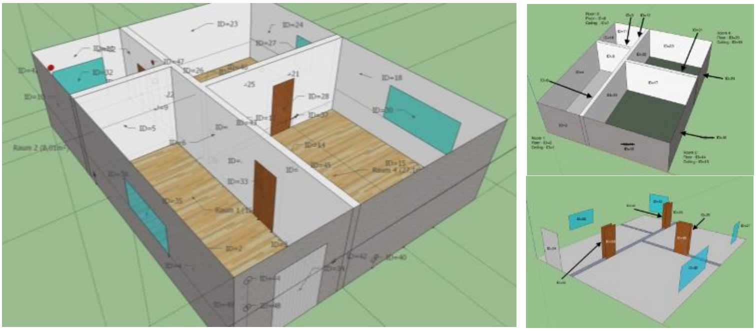

Figure 5-1: Google SketchUp model view in three different perspectives of the exemplary four-room apartment (case study 1) and its building elements (IDs)

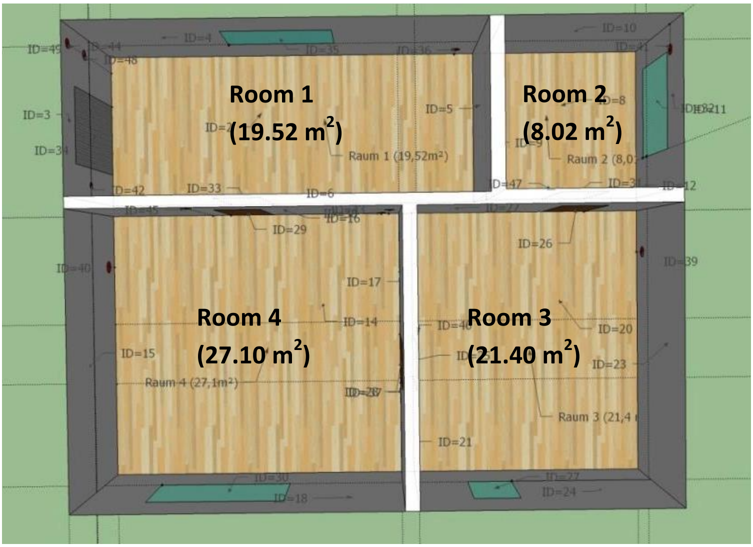

Figure 5-2: Vertical projection (floor plan) with the room numbers and their floor area [m^2] in the Google SketchUp model for the exemplary four-room apartment (case study 1)

Table 5-1: Exemplary OBJ interface structure for faces (f) with data for a fictive four-room apartment

Geometric type (GeoRefType)	Ref vertice 1	Ref vertice 2	Ref vertice 3	Ref vertice 4
f	1	2	3	4
f	5	6	7	8
f	9	10	11	12
f	13	14	15	16
f	17	18	19	20
f	21	22	23	24
f	25	26	27	28
f	29	30	31	32
f	33	34	35	36
f	37	38	39	40
f	41	42	43	44
f	45	46	47	48
f	49	50	51	52
f	53	54	55	56
f	57	58	59	60
f	61	62	63	64
f	65	66	67	68
f	69	70	71	72
f	73	74	75	76
f	77	78	79	80
f	81	82	83	84
f	85	86	87	88
f	89	90	91	92
f	93	94	95	96
f	97	98	99	100
f	101	102	103	104
f	105	106	107	108
f	109	110	111	112
f	113	114	115	116
f	117	118	119	120
f	121	122	123	124
f	125	126	127	128
f	129	130	131	132
f	133	134	135	136
f	137	138	139	140

Beyond the interface data from CSV/OBJ files (see also Appendix III), the proposed model requires user input on several general and project-specific building information of the deconstruction project. For that purpose, the model user can enter data such as building name, address, community and state as well as building type[2], construction type, year/period of construction, number of stories, number of housing units (apartments), roof style, foundation style and the building size (gross volume, gross area) into an user interface (see Figure 5-4). This data is mainly collected for later project documentation, except for the construction type and the style of foundation which are used in the subsequent inventory calculations. Style of roof is not used here, as both case studies are building stories where no roof is considered.

As can be seen in the graphical user interface displayed in Figure 5-4 (left part), the following information on the example case study 1 are assumed and the fictive apartment is classified as:

- Bauwerksuntergruppe (building subgroup) = ‘Wohngebäude’ (residential building),
- Bauwerksklasse (building class) = ‘Wohngebäude ohne Wohnheime’ (residential buildings without dormitory),
- Bauwerksunterklasse (building subclass) = ’Einfamilienhaus’ (single-family house),
- Gebäudetyp (construction type) = ‘II: Massivbau – Mauerwerkwand-Holzträgerdecke’ (masonry with wooden ceiling).

A building age is not known and the respective data field is left empty. There is just a single story considered, including a single apartment unit. For simplicity reasons, a cellar is not assumed and instead of a foundation the floor[3] is assumed to be a standard timber slab like the ceiling.

[2] Information based on standards for residential, non-residential, and health care buildings (or similarly constructed buildings) are available in the model. Standards’ information regarding other building or construction types have to be added to the model if required.

[3] In the case of a base plate or foundation slab, a floor slab with a protrusion of twice the wall thickness would be assumed.

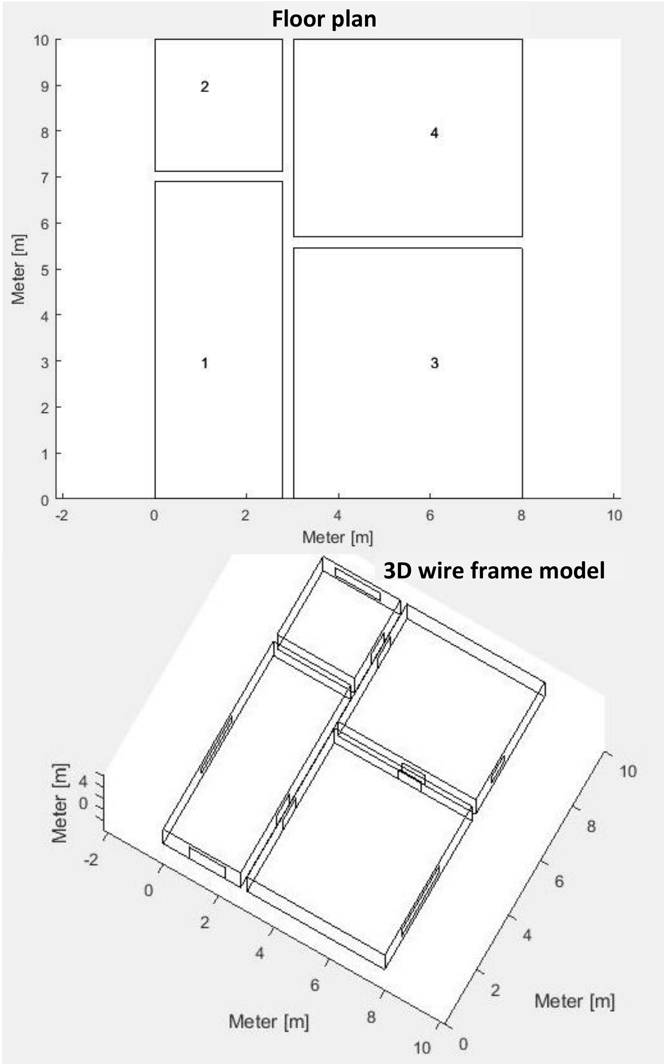

Figure 5-3: Vertical projection (floor plan) of internal walls with room numbers (top) and 3D wire frame model view in isometric projection (bottom) of the exemplary four-room apartment (case study 1) in the deconstruction planning model

The ceiling is assumed to be a timber slab, which is based on the construction type information that was entered by the user and which coincide with the CSV/OBJ information. The roof style is considered a flat roof although further calculations on the ceiling or roof covering from above are not made here. A gross volume or gross area information is not known and thus not entered in the user interface.

Table 5-2: General building information regarding building elements, vertices and faces (case study 1)

General Information	Structural building elements	Interior fitting building elements
4 rooms 49 building elements 154 points/vertices 35 faces	4 ceilings 4 floors/foundations 16 walls	4 windows 4 doors 14 electrical outlets, switches, distribution boxes (TEQ Power)

In the center part of the graphical user interface in Figure 5-4, information on the technical equipment's' characteristics and connection points to public supply lines can be entered. In case study 1, only technical equipment of power supply is considered for simplicity. The main apartment and building power ports coincide and are given in the CSV/OBJ data at (x=0.30; y=0.00; z=1.50) in the coordinate system with the parent wall ID=3, which is directly located next to the apartment entrance door. If the technical equipment port information is not entered via the user interface, the ports might be recognized and transferred automatically via CSV/OBJ interface or the model assumes the origin of the coordinate system to be the central TEQ connection point.
The right part of Figure 5-4 shows a list of already imported rooms from the CVS/OBJ data set, their room type (if this can be determined via recognized building elements in the respective rooms) and their floor covering based on CSV interface information.

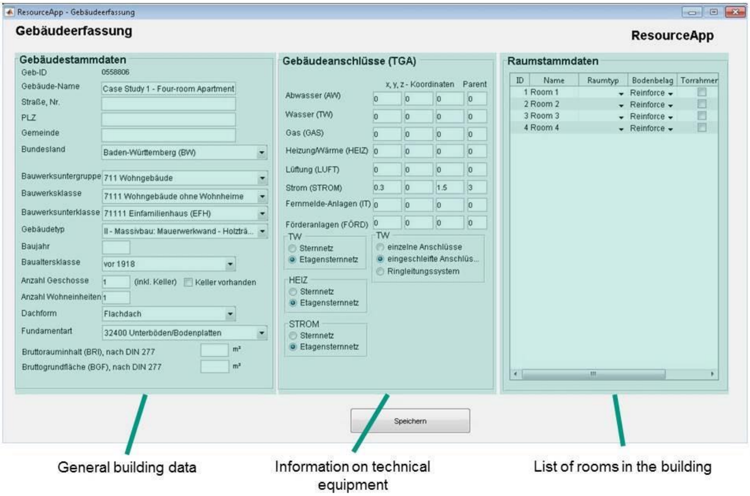

Figure 5-4: Graphical user interface for general building information with exemplary information on case study 1

Further building information and project parameters can be entered similarly via user interfaces or via Microsoft Excel interface. The kind of information that can be entered or varied is shown in the following Figure 5-5.

Similarly to Figure 5-4, the user can enter building element property information for the respective deconstruction project in a graphical user interface. Based on information from standards and literature, dropdown menus and sliders provide default values but also allow the modification to preferred values. Here, the default information is based on extensive researches of German building and construction standards and related literature. The parameters were completed and reviewed by project partners from the deconstruction and remediation industry.

The left hand side of Figure 5-5 shows average material densities [kg/m³] per material, which is further classified into a mineral fraction, an inorganic fraction, an organic fraction and a composites' fraction. The model calculates building element masses with the default material densities

(see section 4.3.2 for the calculation routine), if the user does not change the value. The material density values are standard values and can be found e.g. in (Schultmann 1998). In case study 1, the default material density values are considered.
In the upper center and right part of Figure 5-5, general parameters for the calculation of reinforcements and frames can be selected by the user. In this case study, the masses of reinforcements are calculated via percentage value per m². The calculation of the opening frame volumes is done by percentage of the openings surface multiplied by the frame thickness.

In the main center part of Figure 5-5, the user can adjust model parameters regarding the structural building elements of walls (DIN 331, 332, 341, 342), ceilings (DIN 351), floors and foundations (DIN 324, 322). Wall parameters include wall thicknesses for interior and exterior walls, reinforcement parameters for reinforced concrete walls, timber share parameters for timber-framed walls, and wall covering thicknesses (here: exemplary implementation for tiles and plaster). Ceiling parameters include ceiling thickness, reinforcement parameters and thickness of the ceiling covering plaster. Floor parameters include the same parameters as ceilings, except for different coverings and their thicknesses (artificial concrete stone, tiles, and PVC). Foundation parameters consist in the foundation height (thickness) depending on the foundation type and include the foundation reinforcement parameter. Case study 1 is assumed to be an apartment in an apartment block, with its ceiling and floor as slabs (no roof, no foundation), so that the half ceiling and floor thickness is calculated.

The provided default values for wall parameters such as wall thickness of exterior and interior walls are based on typical values in DIN 4172:1955-07. Similarly, the thickness values for slabs (floors and ceilings) are taken from literature[4].

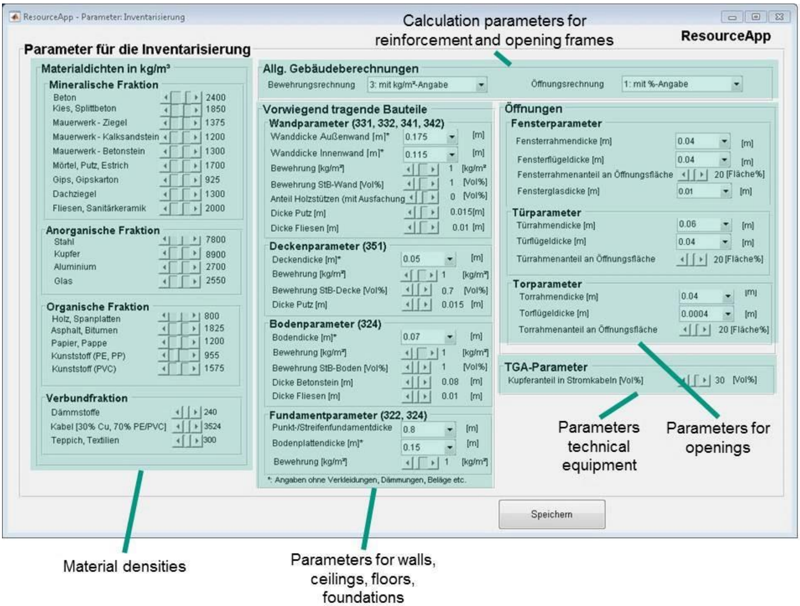

Figure 5-5: Graphical user interface for building element properties (material densities, dimensions, reinforcements)

Reinforcement parameters are not relevant in this case study due to the assumed cellular concrete and timber materials and the lacking of reinforced concrete building elements. However, in case study 2 the reinforcement calculation is described in detail (see section 5.2.1).

4 For example, in DIN 1992-1-1,9.3.2(1), p. 169, 0.20 m is the minimal value for laterally reinforced slabs. In this case study, the thickness value is set as default although timber slabs are assumed because no suitable standard values were found in literature and standards.

In the right part of Figure 5-5, inventorying parameters of openings (windows, doors and gates) are listed with their frame thickness, their wing thickness, their frame percentage with respect to the opening surface and the windows' glass thickness. The default values of openings in the right column of Figure 5-5 are based on measured values in a standard office room with timber-framed doors and windows, but can also be manipulated by the user. In this case study 1, standard frames width values of 0.04 m for windows and 0.06 m for doors are assumed. Furthermore, window and door wing thickness are assumed to be 0.04 m in both cases and the percentage of window and door wing frame is assumed to be 20%. As there are no gates in this case, the parameters of gates are not relevant. Furthermore, in the lower right part of Figure 5-5 the percentage of copper in usual electrical wiring can be selected. In this case, 30% were selected due to recommendation of practitioners' experiences. This constitutes a rather low value, as scrap merchants consider 38% as a standard value for the copper percentage in electrical wires. In Table 5-3, the considered parameters in this case study can also be seen.

Table 5-3: List of inventorying parameters used in the exemplary four-room apartment (case study 1)

Model parameters	Unit	Model parameters	Unit
Foundation slab thickness	0.20 m	Window frame percentage	20%
Foundation slab reinforcement	1 kg/m²	Window frame thickness	0.04 m
Wall thickness, exterior	0.24 m	Window glass thickness	0.01 m
Wall thickness, interior	0.24 m	Door frame percentage	20 %
Ceiling slab thickness	0.2 m	Door frame thickness	0.06 m
		Copper rate	30%

Furthermore, project-related data of deconstruction activity durations per building element type and deconstruction mode as well as activity costs and mode and resource applicability are imported via MS Excel. These parameters can be easily adapted by the user. Stored default data of deconstruction activities' durations coefficients are provided in minimum, expected and maximum values and are taken from literature such as (DBU 2014; Deutscher Abbruchverband e.V. 2015) and are reviewed and cross-checked by experts during research projects in the year 2014[5]. This data is imported and presented to the model user in a third graphical interface (Figure 5-6).

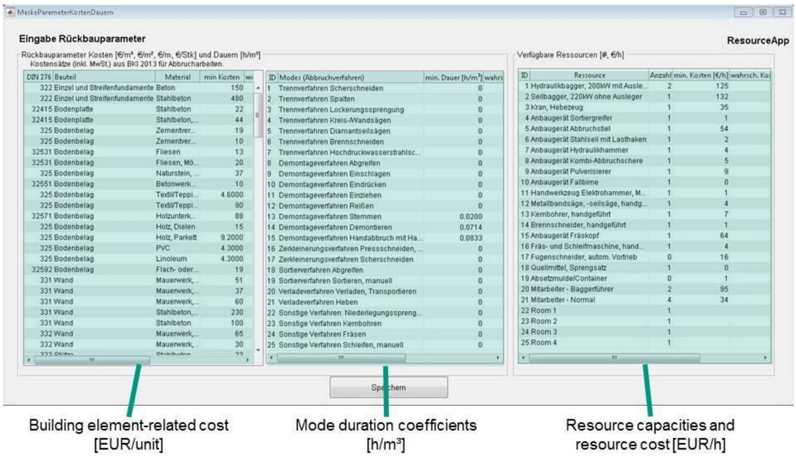

Figure 5-6: Graphical user interface for deconstruction project parameters of building element deconstruction costs, mode duration coefficients and resource capacities and resource cost

Furthermore, in the left column of Figure 5-6 the model user can see the minimum, expected and maximum cost parameters per building element. In the current implementation the mean minimum, the mean expected and the mean maximum value of all building elements with the same DIN276 number are used for cost estimation. Here, the values' units depend on the building element type, e.g. wiring is calculated in EUR/m, while floor covering is calculated in EUR/m². In the center

[5] For further verification of the data, also a measurement of activity durations can be performed, e.g. according to the REFA method.

column of Figure 5-6, the 25 possible activity modes are listed (see also Table 5-4) with the minimum, expected and maximum duration coefficients in h/m³. As only deconstruction activities are considered, this reduces the number of modes to nine. These values are multiplied with the building element volumes from the building inventory to calculate activity durations. The right column in Figure 5-6 shows the renewable resources that are planned in case study 1 together with their capacity and minimum, expected and maximum cost per hour [EUR/h]. The user can change his resource capacities that are available for the current deconstruction project planning. Also, the rooms are listed here as renewable resources but their use is not associated with additional cost. The locations' capacity is automatically set to one. However, if locations allow multiple activities at the same time, the capacity of the respective location can be adapted by the model user in the right column of Figure 5-6. The resource availability and capacity is assumed to be constant over project makespan.

Also, matrices that reflect the technical suitability of building elements-material combinations to deconstruction modes were compiled based on literature and included in the model. Necessary for the inventorying are a 'mode-building' element applicability matrix, a 'mode-material' applicability matrix and a 'mode-resource' applicability matrix that are based on literature (Deutscher Abbruchverband e.V. 2015). The 'mode-building' element and the 'mode-material' applicability matrices are binary matrices that describe the applicability of all used modes to the building elements or respective materials and follows the state of the art technology.

The 'mode-resource' applicability matrix is shown in Table 5-4 and is explained in the following. Table 5-4 shows the potential modes as well as their resource assignment and their capacity in case study 1. As well, the required resources demand per time unit is shown. Due to multiple possibilities to conduct activities in the deconstruction context, the activities are classified in to six main types (see Figure 4-11), that are shown in the first row. For, simplicity reasons, only deconstruction activities (see grey center columns in Table 5-4) are considered in this example, which include eight different activity modes (grabbing, hammering, pressing, pulling, tearing, mortising, disassembling, manual deconstruction).

Table 5-4: Resource capacities and 'activity-mode-resource' applicability matrix

			separation							deconstruction									crush.	sort-ing		transp.		others			
ID	**Resources** (*: with hydraulic excavator)	**Resource availability case study 1**	Shear cutting	Splitting	Loosening blasting	Circular saw	Diamond rope saw	Flame cutting	High pressure water jet cutting	Grabbing	Hammering	Pressing	Pulling	Tearing	Mortising	Disassembling	Manual deconstruction	Pressure cutting, Pulverizing	Shear cutting	Gripping	Sorting, manual	Loading, Transporting	Loading, Hoistering	Controlled demolition/blasting	Core-Sampling	Milling	Grinding
1	Hydraulic excavator, 200kW	2	1	0	0	0	0	0	0	1	0	1	1	1	1	0	0	1	1	1	0	1	0	0	0	1	0
2	Cable excavator, 220kW	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Crane, hoist, 63tm, 2400 kg	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
4	Attachment sorting grab*	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
5	Attachment demolition stick*	1	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Attachment steel cable*	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Attachment hydraulic hammer*	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
8	Attachment combi-cutter/scissors*	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
9	Attachment crusher*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
10	Attachment steel mass	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Hand-held electric hammer	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
12	Hand-held wire saw	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Hand-held core drill	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
14	Hand-held flame cutter	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Attachment cutting head*	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
16	Hand-held grinding machine	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
17	Water jet cutter	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Swelling agents, explosives	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
19	Container	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
20	Staff: Machine operator	2	1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1	1	0	1	1	0	0	1	0
21	Staff: Normal Worker	4	1	2	3	2	2	2	2	1	1	1	1	1	1	3	1	1	1	1	2	1	4	3	2	1	2

5.1.2 Part A: Building inventorying and scenario construction

In the case study apartment, 49 building elements of windows, doors, electrical outlets and distribution boxes are included. The combinatorial scenario generation of every possible building element and material combination result in about 500.000 scenarios and a problem size, that is too large to solve. Thus, a smaller set of scenarios is generated according to section 4.3.

Figure 5-7 and Figure 5-8 show the first model results. Here, the gross floor area and the gross volume of the case study apartment is automatically calculated with 80 m² regarding only the interior wall measures (GFA) and with 86 m² when also exterior measures are considered (GFA_{ext}). The calculated gross volume is 208 m³ or respective 240 m³, when the exterior dimensions are considered. As there are no niches, recesses or protrusions, this value exactly calculates the GFA and GV based on the CSV/OBJ data and the model parameters.

Then, the building elements and materials are inventoried with their volumes and masses. In the inventorying step, several aggregation levels are differentiated. The aggregated inventory of the examined building is structured in the same manner as the CSV/OBJ data including all recognized building elements of the optimal sensor. This inventory includes the material information of the main building material, e.g. brick in the case of brick masonry wall. The detailed inventory includes both recognized and assumed building elements including major components of building elements that consist of different materials separately (such as foundations or reinforcements) with all their material information, room reference and minimum and maximum building element volume (see Table 7-5, Appendix IV).

In this inventory, all building elements are depicted in their ‘smallest’, varietal units so that each element can be assigned to a single material (e.g. wall reinforcement made of steel, wall matrix material made of concrete). The created building inventory is used to constitute the initial

observation for the following scenario construction (see section 4.3.6). Table 7-5 shows the detailed building element inventory of the case study 1 apartment, including the walls, floor, ceiling, windows, doors and technical equipment of electrical power supply (TEQ Power). Based on the recognized building elements, DIN numbers are assigned to the building elements and surface, volume and mass are assigned or calculated. Assigned values are a zero surface of TEQ Power elements and a standard value of 0.2 kg per electrical outlet. Also, the material information of the building elements is given and the reference room where the building element is located is reasoned.
Furthermore, material-specific inventories and an aggregated material inventory are compiled with their minimum volumes, their expected volumes based on the sensor data and the user input and the maximum volumes per material (see Table 5-6).

For the scenario construction, the building element properties are varied according to the scenario construction described in section 4.3. The baseline scenario (no. 14) includes: timber ceilings, timber floor, cellular concrete brick masonry walls, timber-framed windows and doors (see expected material in Table 5-5). The electrical equipment is assumed to be consisting mainly of PVC except for the copper share in the conductive part of the wiring and the large aluminum distribution box of the apartment. For the best and worst material scenarios, the materials from ceilings, floors, walls, windows and doors are varied, e.g. the floor in the best case (regarding the deconstruction time) is made of artificial stone and in the worst case of reinforced concrete (see Table 5 5). The materials of the electrical equipment (DIN 44411-44441) are not changed. This results on average in 3.33 potential material variations per building element (with TEQ elements). Without TEQ elements this value is considerably higher with 5.20 materials per building element.
Table 5-6 includes the material inventory that aggregates the detailed building element inventory (Table 7-5) according to the inherent materials into 29 material categories. In this small example, the inventory is

reduced to the inherent material categories. And, the material inventory can be further aggregated to the assigned recycling and disposal paths (see Table 5-7). Table 5-7 shows the minimum, expected and maximum deconstruction masses that are designated to one of the listed categories of material recycling (secondary raw material use), energetic recycling (combustion), backfilling (e.g. onsite or in mining) and disposal on disposal sites.

The minimum and maximum values are calculated according to section 4.3, where mainly the building element thickness is varied in the range of standard construction values. The material density is not varied. The expected values are based on sensor information, which can themselves be subject to uncertainty, which cannot be quantified here. Based on the aggregated material inventory, the recycling and disposal cost are calculated (see section 5.1.3).

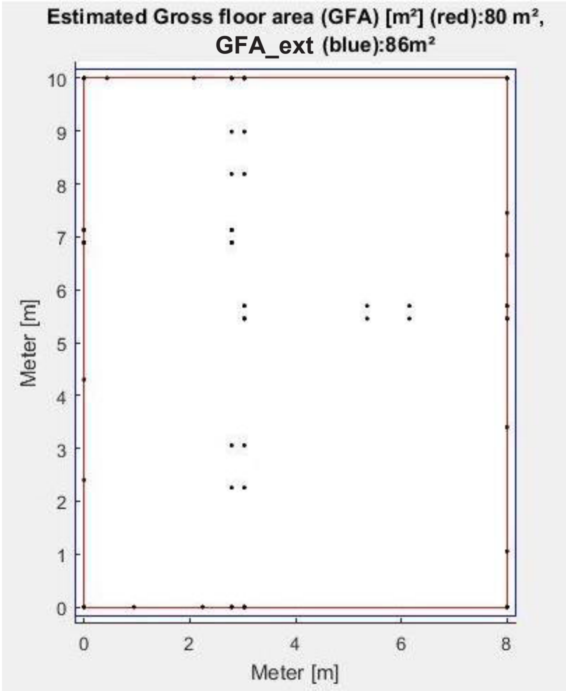

Figure 5-7: Gross floor area of the four-room apartment (case study 1), blue: outer envelopment, red inner envelopment

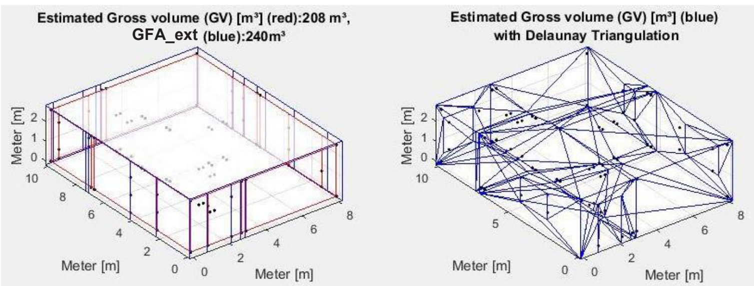

Figure 5-8: Gross volume of the four-room apartment (case study 1), blue: outer envelopment, red inner envelopment

Table 5-5: Material variations in the scenario construction of case study 1

DIN 276	Building element	Best material	Expected material	Worst material
324	Floor	Artificial resinate stone	Timber	Reinforced concrete
331	Exterior walls	Natural masonry	Cellular Concrete	Timber
341	Interior walls	Natural masonry	Cellular Concrete	Timber
351	Ceilings	Timber	Timber	Reinforced concrete
3341	Doors	Steel	Timber	Glass
3342	Windows	Steel	Timber	Timber
44411	TEQ Power Wiring	Cable	Cable	Cable
44421	TEQ Power Small Distribution Box	PVC	PVC	PVC
44422	TEQ Power Large Distribution Box	Aluminum	Aluminum	Aluminum
44441	TEQ Power Outlets (Switch, Socket)	PVC	PVC	PVC

For the scenario construction, the building element properties are varied according to the scenario construction described in section 4.3. The baseline scenario (no. 14) includes: timber ceilings, timber floor, cellular concrete brick masonry walls, timber-framed windows and doors (see expected material in Table 5-5). The electrical equipment is assumed to be consisting mainly of PVC except for the copper share in the conductive part of the wiring and the large aluminum distribution box of the apartment. For the best and worst material scenarios, the materials from ceilings, floors, walls, windows and doors are varied, e.g. the floor in the best case (regarding the deconstruction time) is made of artificial stone and in the worst case of reinforced concrete (see Table 5-5). The materials of the electrical equipment (DIN 44411-44441) are not changed. This results on average in 3.33 potential material variations per building element (with TEQ elements). Without TEQ elements this value is considerably higher with 5.20 materials per building element.

Table 5-6: Aggregated material inventory of four-room apartment (case study 1) for the baseline scenario

Building element material	min. mass [kg]	exp. Mass [kg]	max. mass [kg]	exp. Cost [EUR/kg]
Masonry, Cellular concrete	27593	41731	71847	0.02
Aluminum	4	4	4	-0.91
Glass	76	151	302	0.02
Timber (treated)	2482	7370	11359	0.1
Plastics (PVC) (excl. wires)	2	2	2	0.23
Cable	7	7	7	-0.67

Table 5-7: Recycling paths with estimated material masses [t] for case study 1 for the baseline scenario

Recycling paths	Minimum mass		Expected mass		Maximum mass	
	[t]	[%]	[t]	[%]	[t]	[%]
Material recycling	0	0.0	0	0.0	0	0.0
Energetic recycling	2	6.7	7	14.3	11	13.3
Backfilling	28	93.3	42	85.7	72	86.7
Disposal	0	0.0	0	0.0	0	0.0
Total [t]	**30**	**100.0**	**49**	**100.0**	**83**	**100.0**

5.1.3 Part B: Deconstruction project scheduling and optimization

In this model part, deconstruction activities and their durations are derived from the previously calculated building elements and are grouped to activity sets[6] for each scenario. The activity duration derivation and the grouping is described in section 4.4.1 in detail.

In case study 1, building elements are grouped by their building element types and trades, e.g. interior and exterior walls into ‘walls’, or electrical outlets, lamps and switches into ‘TEQ Power’ of all electrical equipment in a room. Windows and electrical equipment are room-wise grouped into deconstruction activity sets, while the building elements doors,

6 Activities and activity sets are used synonymously in the following as they have the same properties in the scheduling problem.

ceilings, walls and floors/foundations are grouped level-wise. As in case study 1 there is only a single level, deconstruction activities of the single building elements are aggregated into a single activity per building element type. In this case study, 15 activities are derived that include the dummy project start and end activities. The remaining 13 activities are the deconstruction of foundations, floor coverings, walls, ceilings, doors, windows per room and the technical equipment for power supply per room. Table 5-8 shows the list of scheduled activity sets in case study 1, with their activity durations [h] in the 9 considered deconstruction modes. The activity durations per activity mode are derived from typical performance indicators [h/m³, h/m², h/m, h/piece] and resource demands for deconstruction techniques in literature (Lippok and Korth 2007; Rentz 1993; Schultmann 1998; Seemann 2003; Weimann et al. 2013; Willkomm 1990) and expert information from research projects.
The scheduling of the 15 activity sets follow predefined zero-lag finish-start precedence due to technical constraints, organizational or logistic issues that follows the general deconstruction precedence presented in Figure 2-8 in chapter 2. For example, different trades are differentiated regarding the building fittings and technical equipment or top-down deconstruction of the main structure are applied due to static reasons. Figure 5-9 shows the 22 precedence relations considered in case study 1. After project start, in the following deconstruction activities all doors, windows and electrical equipment are removed from the building. Then, the floor covering is deconstructed. After these buildings' interior fittings are deconstructed, the whole structure is demolished from top to bottom including ceilings, walls and the foundation or floor slab of the exemplary apartment.
In this case study, nine modes for deconstruction activities with 25 different renewable resources consisting in machines, staff and locations (#4 rooms) were used. The time granularity of the model was selected with ten minutes. Although the problem size seems relatively small, the problem was not solvable for a time slice of five minutes due to an out-of-memory error in scenario 27 due to a large model decision matrix

(>> 6 GB). For larger problem sizes, the time granularity has to be further reduced to ensure model solvability. This comes along with a decreased differentiation of the activity durations and thus a more inaccurate schedule and resource assignment.

To further characterize the scheduling problem, it can be stated that per deconstruction activity on average 3.78 potential modes are possibly applicable on the inherent building elements and on average 3.78 different resources (without locations) are necessary to perform a mode. Furthermore, a resource factor of $RF = 0.237$ and an average resource strength $RS = 0.012$ over all resources and modes demonstrate the resource scarcity in this case study problem. As both values are rather low, this indicates a scheduling problem that is rather difficult to solve. The restrictiveness RT depicts the degree of parallel activities in an acyclic project network. In this case study, the restrictiveness value is $RT = 0.902$, reflecting the high parallelism of deconstruction activities and the rather difficult scheduling problem of deconstruction activities in case study 1.

Table 5-8: Deconstruction activities and their durations in case study 1 for the best, the base and the worst case scenario (none = all rooms, R1 = Room 1, R2 = Room 2, R3 = Room 3, R4 = Room 4)

		Activity duration [h]																										
ID	Deconstruction activity	Best case scenario (scenario no. 1)									Baseline case scenario (scenario no. 14)									Worst case scenario (scenario no. 27)								
	Mode	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1	Start	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Foundations	0	0.36	0	0	0	0	0.00	0.00	0	0	1.32	0.02	0	0	0	0.02	0.03	0	0	11.04	0.12	0	2.30	7.67	0.03	0.24	1.92
3	Floor Covering	0	0.14	0	0	0.10	0.36	0.00	0.00	0	0	2.59	0.02	0	0	0	0.01	0.02	0	0	21.98	0.08	0	4.61	15.35	0.02	0.16	3.84
4	Walls	0.41	0.31	0	0	0	0.12	0.00	0.00	0	0.41	0.67	0.39	0.45	0	1.71	0.03	0.06	0	0.67	5.63	8.44	8.37	0	0	2.41	0.14	0
5	Ceilings	0.28	0.21	0	0	0	0.08	0.00	0.00	0	0.20	0.31	0.18	0.22	0	0.84	0.01	0.02	0	0.40	3.45	5.18	5.05	0	0	1.48	0.25	0
6	Doors	0	0.09	0	0	0.07	0.23	0	0	0	0	1.69	0.03	0	0	0	0.02	0.03	0	0	14.15	0.02	0	2.97	9.90	0.01	0.04	2.47
7	Windows, R1	0	0	0	0	0	0	0.00	0.00	0	0	0.02	0.01	0	0	0	0.01	0.01	0	0	0.06	0.09	0	0	0	0.02	0.17	0
8	TEQ Power, R1	0.01	0	0	0	0	0	0.00	0.00	0	0.01	0	0	0	0	0	0.00	0.01	0	0.01	0	0	0	0	0	0.01	0.05	0
9	Windows, R2	0	0	0	0	0	0	0.00	0.00	0	0	0.05	0.03	0	0	0	0.02	0.03	0	0	0.08	0.12	0	0	0	0.03	0.23	0
10	TEQ Power, R2	0	0	0	0	0	0	0	0.00	0	0	0	0	0	0	0	0	0.00	0	0	0	0	0	0	0	0	0.00	0
11	Windows, R3	0	0	0	0	0	0	0.00	0.00	0	0	0.05	0.03	0	0	0	0.02	0.03	0	0	0.09	0.13	0	0	0	0.04	0.26	0
12	TEQ Power, R3	0	0	0	0	0	0	0	0.00	0	0	0	0	0	0	0	0	0.00	0	0	0	0	0	0	0	0	0.00	0
13	Windows, R4	0	0	0	0	0	0	0.00	0.00	0	0	0.03	0.02	0	0	0	0.01	0.02	0	0	0.04	0.06	0	0	0	0.02	0.11	0
14	TEQ Power, R4	0	0	0	0	0	0	0	0.00	0	0	0	0	0	0	0	0	0.00	0	0	0	0	0	0	0	0	0,00	0
15	End	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

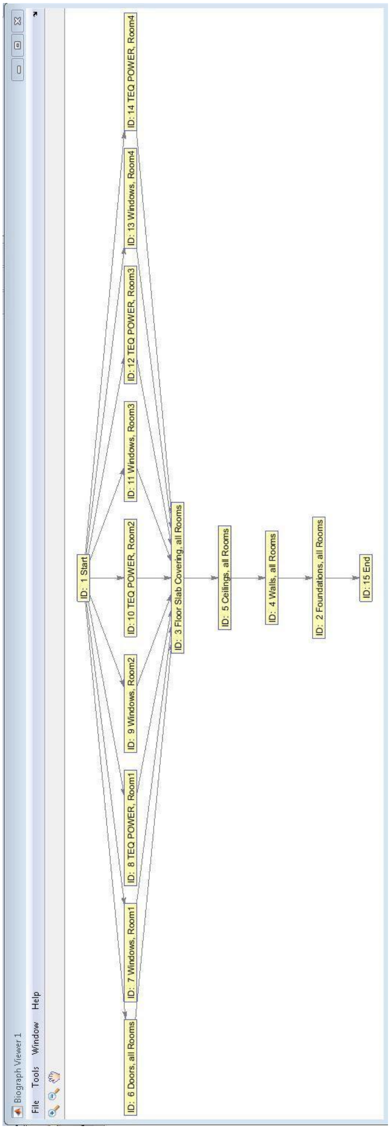

Figure 5-9: Deterministic directed acyclic precedence graph with 15 deconstruction activity sets grouped per room (ID: 7, 8, 9, 10, 11, 12, 13, 14) or over all rooms (ID: 2, 3, 4, 5, 6) for case study four-room apartment

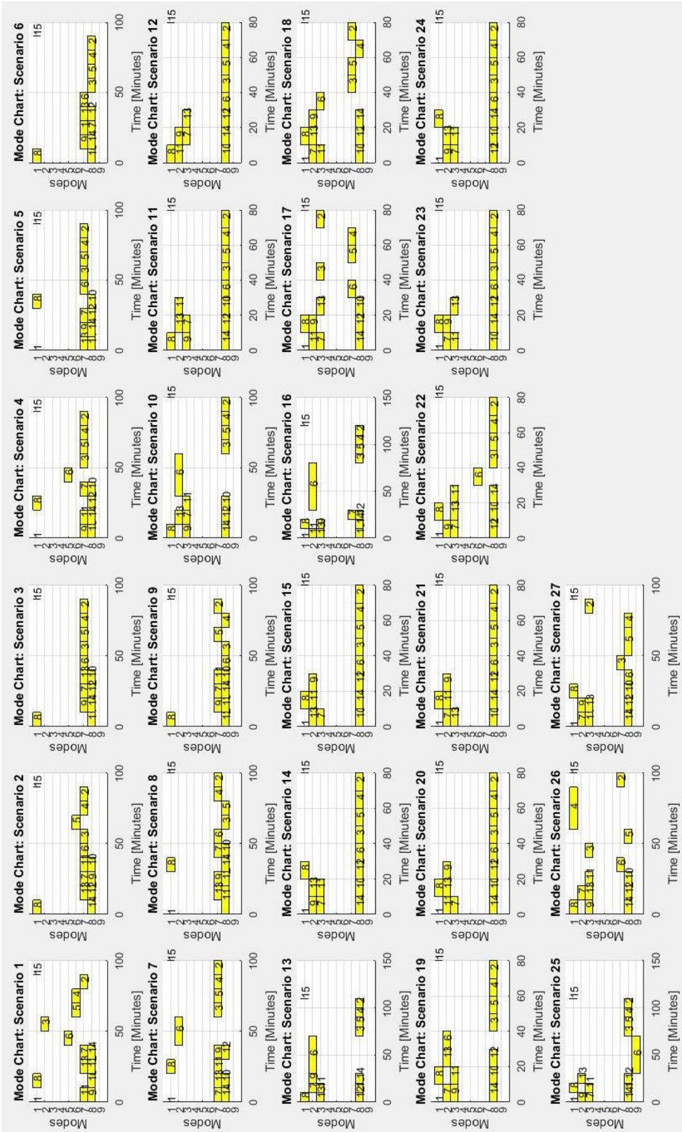

Figure 5-10: Gantt charts with optimal modes (y-axis) of all case study 1 activities in each scenario respecting precedence and resource constraints over project time t (x-axis)

The resulting schedules represented by Gantt charts of the baseline scenario can be seen in Figure 5-10 and are shown per scenario in Figure 5-11 and Figure 5-12. Figure 5-10 shows the optimal schedules in all 27 scenarios with differing mode selections of the 15 deconstruction activities. The named modes and their resource demand are detailed in Table 5-4. Figure 5-11 shows the Gantt chart of baseline scenario 14 without precedence relations (left) and with precedence relations that are represented by dashed arrows and earliest start and latest completion time frames (horizontal lines with vertical markers) (right). Figure 5-12 shows the mode assignments of all activities (left) and the utilization of the scarce renewable resource ‘location’ (right), where in both diagrams the numbers on the activities represent the activity IDs.

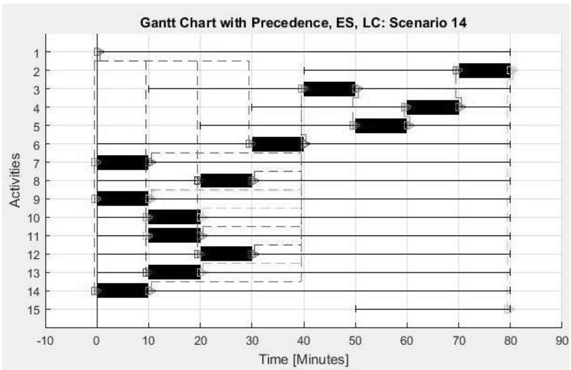

Figure 5-11: Gantt chart of baseline scenario 14 for case study 1 with all activities (y-axis) over project time t (x-axis)

Figure 5-13 shows the resource profile of the optimum schedule in the baseline scenario. The optimum resources are a hydraulic excavator (top left) and a cable excavator (top right) with three different extensions (second row and bottom right), hand-held hammer (bottom left) and machine operator and normal staff (third row). Figure 5-14 shows the deconstruction site locations in case study 1. Here, rooms 1, 2, 3 and 4 are modeled as locations and their capacity profile over project makespan. In figures (Figure 5-13 and Figure 5-14), the resource and location capacities are indicated by the bold black horizontal line. This figure shows both types of deconstruction activities that are either planned per room (e.g. deconstruction of windows) or planned over all locations (e.g. deconstruction of ceilings).

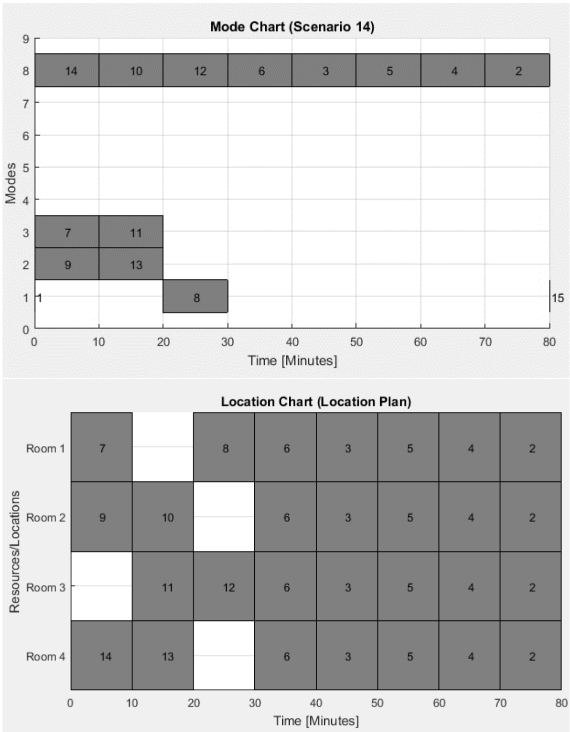

Figure 5-12: Mode assignment chart and location chart for case study 1 in the baseline scenario for all activities

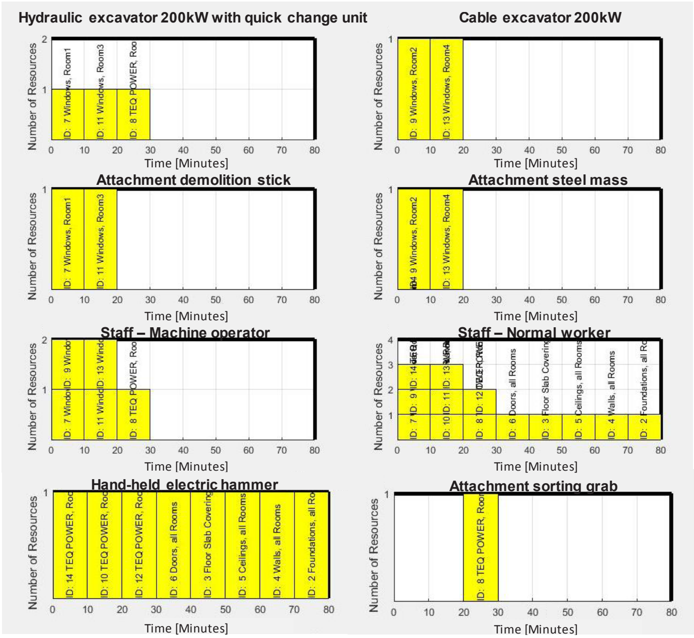

Figure 5-13: Resource profile and the resource capacity (horizontal blue line) in the baseline scenario 14 for case study 1

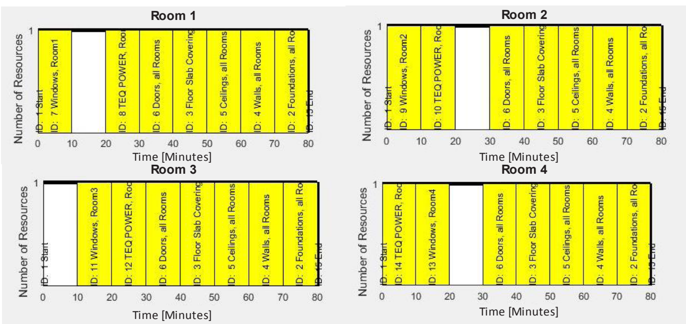

Figure 5-14: Location profile and the location capacity (horizontal blue line) in the baseline scenario 14 for case study 1

The project costs are calculated for case study 1 as described in section 4.4.6 based on the one hand on the resulting cost from the optimal project schedule per scenario and on the other hand on the recycling revenues and disposal cost per scenario. In German construction and deconstruction industry, machinery depreciation is calculated according to German BGL Baugeräteliste. These values of expected service life in years, the idle months and the proposed depreciation rates per resource are used in the cost estimation of both case studies of this research contribution (BGL 2015)[7]. The depreciation rate only applies to machinery and equipment and not to staff or locations. For simplicity, this value is calculated on hourly basis. Other supply costs include the cost for fuels and lubricants for operating the supporting/carrier equipment for the time it is used in the project and are usually calculated based on equipment-specific data and tables but are neglected in the cost calculations so far. In the second way of calculating $C_{var,j}{}'$, the BKI deconstruction cost factors $c_{U(e')}$ are applied (BKI 2014) that were modified by practitioners for the region of the application case in Niedersachsen in Germany, but that might vary between regions.

To calculate the recycling and disposal costs of the project, the designated recycling and disposal of fractions follow the hierarchical recycling paths of KrWG. In the model, the assignment of the building element masses to recycling and disposal fractions follow the state-of-the-art technology and is dependent on the respective material. Here, fractions of metal (steel, copper, aluminum, electric wires) and glass are assumed to be recycled and to gain recycling revenues. Material fractions of timber, textiles, and plastics (PE, PVC) are assumed to be energetically used and combusted. Mineral fractions of concrete, screed, mortar, plaster, tiles, bricks and artificial stones are assumed to be backfilled onsite, in road construction or in mining. Materials and building elements made of gypsum, insulation materials, asbestos and other hazard-

[7] A more detailed description of the data sources and cost calculation can be found in sections 4.4.6 and 5.2.3.

ous materials are assumed to be deposited in landfills. Energetic use, backfilling and disposal are calculated at the current cost per ton [EUR/t]. The recycling and disposal rates are calculated based on the mentioned recycling and disposal assignment of the material fractions for case study 1 and are listed in

For the scenario construction, the building element properties are varied according to the scenario construction described in section 4.3. The baseline scenario (no. 14) includes: timber ceilings, timber floor, cellular concrete brick masonry walls, timber-framed windows and doors (see expected material in Table 5-5). The electrical equipment is assumed to be consisting mainly of PVC except for the copper share in the conductive part of the wiring and the large aluminum distribution box of the apartment. For the best and worst material scenarios, the materials from ceilings, floors, walls, windows and doors are varied, e.g. the floor in the best case (regarding the deconstruction time) is made of artificial stone and in the worst case of reinforced concrete (see Table 5-5). The materials of the electrical equipment (DIN 44411-44441) are not changed. This results on average in 3.33 potential material variations per building element (with TEQ elements). Without TEQ elements this value is considerably higher with 5.20 materials per building element.

Table 5-6. The percentage of the fractions of material recycling, energetic recycling, backfilling and disposal are calculated in relation to the total deconstruction mass. In case study 1, the recycling rate is 13.80 % (separated in 0.35 % secondary raw material recycling and 13.45 % energetic recycling). The disposal rate is 86.20% (86.20 % backfilling and 0 % disposal). As the recycling and disposal fractions are only assumed, and the local and regional recycling options on near construction sites often are not known due to a structural information deficit. Thus, the identified recycling and disposal rates might not necessarily reflect the real values.

The expected disposal costs and recycling revenues in the model are based on actual prices of respective waste fractions as well as raw material and recycling material prices for Niedersachsen (Container-

dienst-regional.de 2016; Schrott.de 2016). These prices may vary depending on international raw material prices or between regions and can only be seen as a sample calculation. Transportation, sorting, or crushing costs are not included yet in the calculated variable deconstruction costs[8] and also container rent is not included yet. Table 5-9 shows the calculated disposal costs and recycling revenues in case study 1 according to formulas (4.52) and (4.53) (related to building elements).
Also, recovery costs of materials per kilogram or ton are calculated. This value is calculated as the amount of the respective material divided by the total project cost. The value can increase the comparability of recovery costs between various deconstruction and recovery projects and the current raw material price. However, as it is only calculated per material, the recycling revenues of other materials are not considered in the recovery costs of a single material.

Table 5-9: Project cost for baseline scenario in case study 1

Project costs	**Minimum project cost [EUR]**	**Expected project cost [EUR]**	**Maximum project cost [EUR]**
Costs for deconstruction activities	17,126.00	22,939.00	30,137.00
Costs for sorting activities	0.00	0.00	0.00
Cost for disposal	602.00	1,496.00	2,903.00
Revenues for raw materials/ recycling	-6.00	-8.00	-10.00
Total project costs	**17,722.00**	**24,427.00**	**33,030.00**

Figure 5-15 shows model results for the baseline scenario of case study 1 with its building element inventory (left), material inventory (center), Gantt chart of the scheduled deconstruction activities (bottom), calculated project duration (right top), calculated project cost (right center) and calculated material recycling, energetic recycling, backfilling and

[8] The interested reader is referred to (Schultmann 1998 pp. 85–101) for details on the calculation and inclusion of these cost.

disposal rates (right bottom). The recovery cost per material can be found in the center table of Figure 5-15 by scrolling to the right.

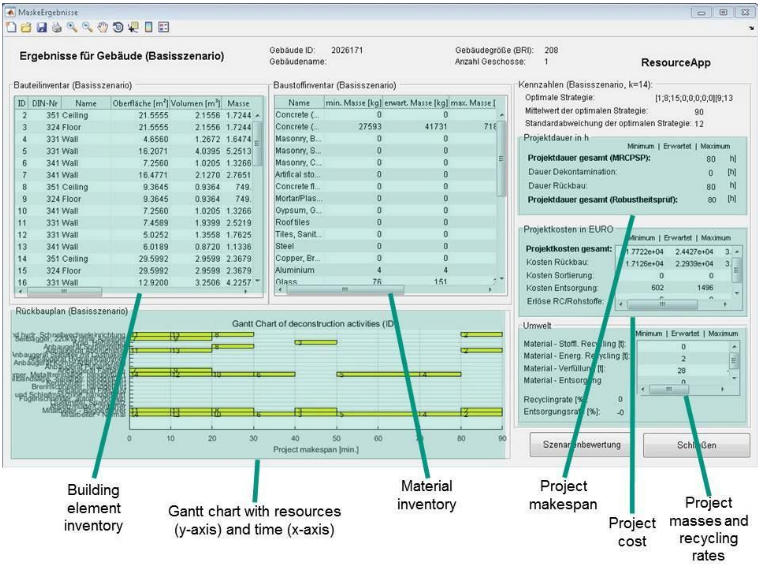

Figure 5-15: Graphical user interface with model results for the baseline scenario of case study 1

Figure 5-16 and Figure 5-17 show the optimum project makespan C_{max} in all scenarios and their resulting project cost. In Figure 5-16, the sorted optimal project makespan distribution over all scenarios is shown. This can be seen as the density function of the optimal project makespan over all scenarios, if the 27 scenarios are assumed to be equally distributed. The numbers in the diagram label the respective scenarios.

Figure 5-17 shows the distribution of optimal project makespan and resulting project cost (according to formula (4.54) related to applied resources) for all scenarios. Here, often a linear relation is assumed in literature which cannot necessarily be stated for the deconstruction project in case study 1. Based on this project makespan distribution, the average project makespan distribution could be calculated if all scenarios are assumed to be equally distributed.

As well, the numbers in this diagram label the respective scenarios. Especially the Figure 5-17 can be used to compare different scenarios and their optimal project schedules and cost with each other. Also, the project deadline (=maximum project makespan) if existent can be depicted by a vertical line, here exemplarily set for 115 time units. And, the project budget (=maximum total project cost) if existent can be represented by a horizontal line, here exemplarily set at 11500 EUR. This provides the decision maker with insights on the expected project durations and the total project costs under different scenarios (site conditions).

Table 5-10: Computational effort of problem construction and problem solution of case study 1 [sec]

Scen. No.	Problem construct. [sec]	Problem solution [sec]	Number of iterations	Scen. No.	Problem construct. [sec]	Problem solution [sec]	Number of iterations
1	3.23	0.39	154	**15**	14.26	1.65	313
2	5.30	0.24	307	**16**	9.36	1.03	173
3	7.34	0.32	132	**17**	17.37	2.05	331
4	4.08	0.17	182	**18**	28.38	3.97	198
5	7.32	0.41	132	**19**	4.11	0.17	328
6	10.63	0.45	230	**20**	6.33	0.30	341
7	10.24	0.38	147	**21**	9.45	0.76	410
8	20.26	1.94	178	**22**	5.04	0.19	240
9	34.02	5.02	322	**23**	7.60	0.50	355
10	4.33	0.15	153	**24**	12.07	1.33	486
11	7.78	0.66	409	**25**	18.12	2.79	119
12	10.82	0.84	491	**26**	137.73	198.61	490
13	5.21	0.19	124	**27**	3179.06	796.80	451
14	9.69	1.17	289				

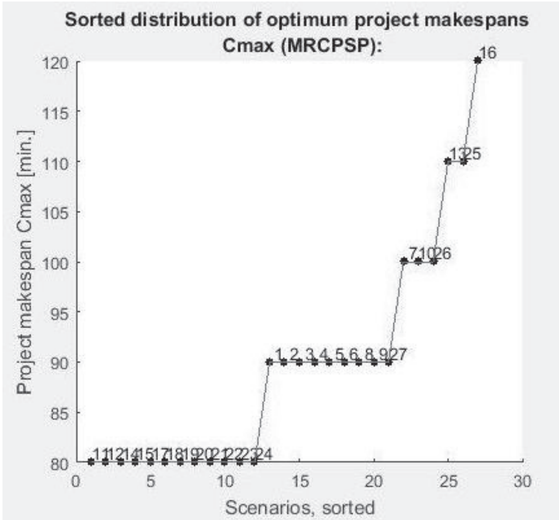

Figure 5-16: Distribution of optimal project makespan C_{max} (MRCPSP) over all 27 scenarios for a scenario comparison

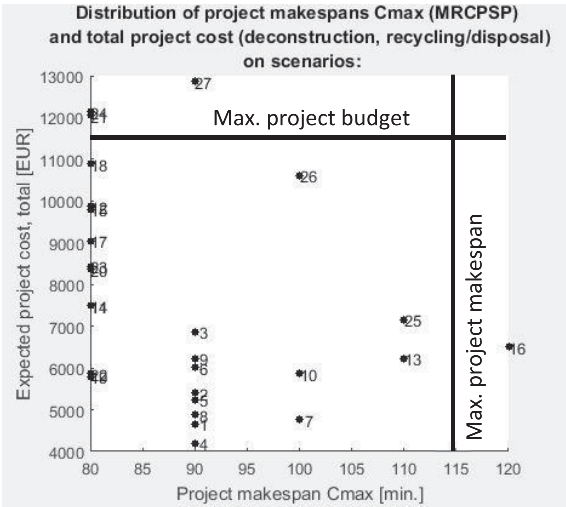

Figure 5-17: Distribution of optimal project makespan Cmax (MRCPSP) and resulting project cost over all 27 scenarios for a scenario comparison

However as discussed already in sections 4.4.4 and 4.7.2, the computational effort to calculate the optimum resource assignment and the minimum project makespan for all scenarios is quite high and strongly depends on the chosen model granularity (activity grouping and time slices). Here, time slices of 10 min where chosen that result in the following problem construction time [sec], problem solution times [sec] and CPLEX iterations (see Table 5-10). In total, the computational effort regarding the solution of the MRCPSP for all 27 scenarios is summing up to about 76 minutes. Table 5-10 shows the detailed computations effort per scenario. On average, 132 seconds are required for the problem construction and on average 77 seconds and 277 iterations are necessary to find the optimal solution with CPLEX solver[9]. However, as can be seen in Table 5-10, the last two scenarios are taking exceptionally longer for their problem construction and problem solution although the problem size regarding the number of activities, resources and locations is the same. This is because in the scenarios 26 and 27 considerably longer activity durations lead to an increased number of time slices.

5.1.4 Part C: Identification and selection of robust deconstruction strategies

In this model part, a robust deconstruction strategy for case study 1 is identified according to the decision makers' risk preference. In case study 1, 27 optimal deconstruction strategies are identified by the model. For this purpose, the identified optimum deconstruction strategies of each scenario from model part B (Figure 5-16) are used to plan each scenario with each optimal deconstruction strategy (stress test). The resulting project makespan C_{max} of all deconstruction strategies and all scenarios is shown in Figure 5-18. Figure 5-18 shows that there are

[9] In this case study, the following default CPLEX options are used: maximum number of iterations (MaxIter): 9.2234e+18, branching strategy (BranchStrategy): 'maxinfeas', maximum solution time (MaxTime): 1.0000e+75 seconds, node searching strategy (NodeSearchStrategy): 'bn'.

single constellations of deconstruction strategies that result in very high project makespans (e.g. strategies 8, 15-20 or 25). However, in the total of 729 constellations (27 strategies x 27 scenarios), these circa 20 cases account for around 3% of all constellations. Figure 5-19 shows the frequency of the deconstruction strategies resulting project makespans over all scenarios in a histogram. Here, in almost all of the scenarios, the deconstruction strategies obtain project makespans that belong to the lowest histogram class. Only in single scenarios, deconstruction strategies generate also higher project makespans.
As described before in section 4.5, the deconstruction industry is rather characterized by risk-neutral to risk-averse decision makers. Risk-averse decision makers define the most robust project schedule either by absolute mini-max (regret) criterion or by the best-performing deconstruction strategy in the worst case scenario. Risk-neutral decision makers prefer a most robust schedule with either a minimum average absolute regret criterion or a minimum Laplace criterion.
In case study 1, the most robust strategy or strategies are defined by the minimum average absolute regret criterion. In this research contribution, the total optimality-robust deconstruction strategy $\Pi^*(z_k)$ is of specific interest, which can be identified by the minimum average deviation from the minimum project duration in all scenarios (absolute regret) (see also section 3.2.4). When the minimum average deviation (absolute regret) for a deconstruction strategy $\Pi\ AR(\Pi(z_k)) = 0$ for all scenarios $z_k \in Z$, this solution comprises a total optimality-robust solution.
The generated deconstruction strategies are shown in Table 5—11 for case study 1 with their calculated robustness measures of average project makespan (C_{max} μ) (under the assumption of equally distributed scenarios), their variance project makespan (C_{max} σ^2), their standard deviation project makespan (C_{max} σ), their μ-σ-rule project makespan (C_{max} μ-σ) and their absolute regret (C_{max} AR). Also, the scenario wherein the deconstruction strategy lead to the best objective value is listed in column 3. The deconstruction strategies itself represent the activities

that are planned in the respective modes (here: # = 9) that are delimited from each other by the rectangular brackets.

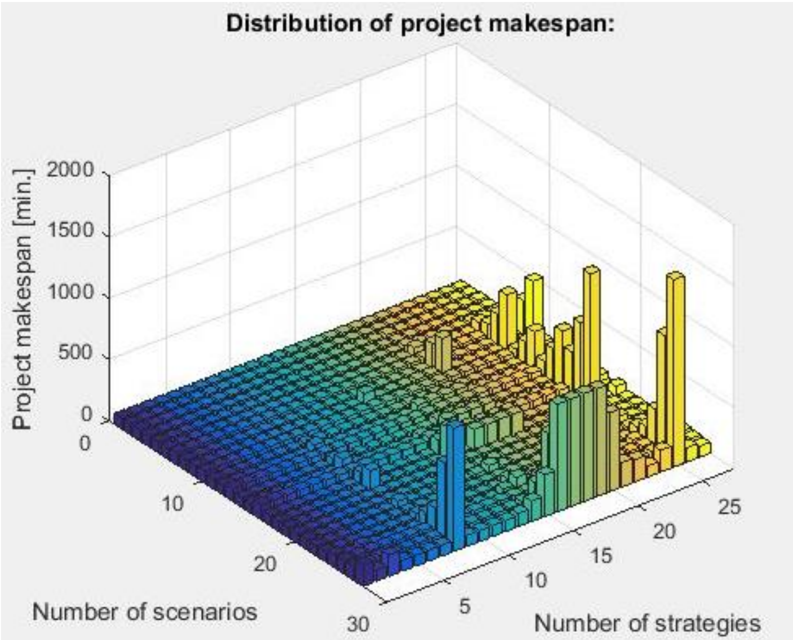

Figure 5-18: Distribution of project makespan [minutes] over all deconstruction strategies and scenarios (stress test) (legend: see also Figure 5-19)

It can be seen in Table 5–11, that there are several deconstruction strategies with a zero average absolute regret, which can all be advised to the decision maker as totally and equally robust deconstruction strategies under the assumed 27 scenarios. In case study 1, these robust deconstruction strategies are $\Pi = \{2, 4, 5, 6, 7, 9, 10, 11, 12, 23\}$.

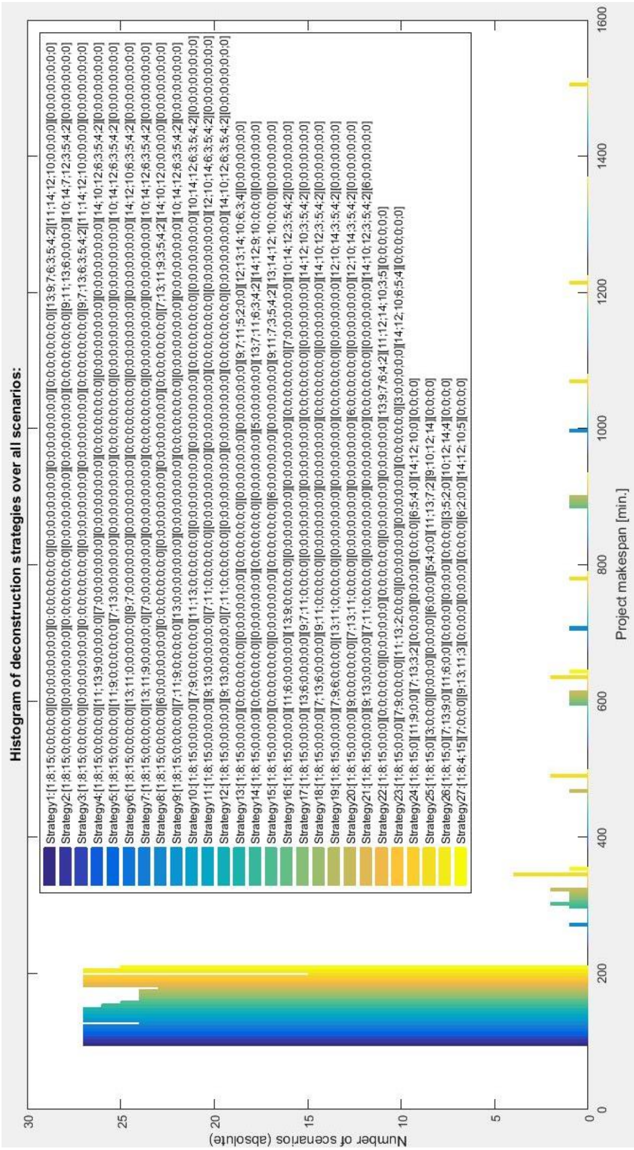

Figure 5-19: Histogram of all deconstruction strategies and their average project makespan (stress test)

Table 5-11: List of deconstruction strategies in case study 1 with summed robustness criteria for each strategy over all scenarios

No	Deconstruction strategy	Opt. in Scen.	C_{max} μ	C_{max} $σ^2$	C_{max} σ	C_{max} μ-σ	C_{max} AR
1	[1;8;15;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][13;9;7;6;3;5;4;2][11;14;12;10;0;0;0;0][0;0;0;0;0;0;0;0]	5	95	400	20	75	129
2	[1;8;15;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][9;11;13;6;0;0;0;0][10;14;7;12;3;5;4;2][0;0;0;0;0;0;0;0]	6	90	144	12	78	0
3	[1;8;15;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][9;7;13;6;3;5;4;2][11;14;12;10;0;0;0;0][0;0;0;0;0;0;0;0]	3	94	400	20	74	128
4	[1;8;15;0;0;0;0;0][11;13;9;0;0;0;0;0][7;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][14;10;12;6;3;5;4;2][0;0;0;0;0;0;0;0]	20	90	144	12	78	0
5	[1;8;15;0;0;0;0;0][11;9;0;0;0;0;0;0][7;13;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][10;14;12;6;3;5;4;2][0;0;0;0;0;0;0;0]	12	90	144	12	78	0
6	[1;8;15;0;0;0;0;0][13;11;0;0;0;0;0;0][9;7;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][14;12;10;6;3;5;4;2][0;0;0;0;0;0;0;0]	11	90	144	12	78	0
7	[1;8;15;0;0;0;0;0][13;11;9;0;0;0;0;0][7;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][10;14;12;6;3;5;4;2][0;0;0;0;0;0;0;0]	15	90	144	12	78	0
8	[1;8;15;0;0;0;0;0][6;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][7;13;11;9;3;5;4;2][14;10;12;0;0;0;0;0][0;0;0;0;0;0;0;0]	7	170	41616	204	-34	2169
9	[1;8;15;0;0;0;0;0][7;11;9;0;0;0;0;0][13;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][10;14;12;6;3;5;4;2][0;0;0;0;0;0;0;0]	21	90	144	12	78	0
10	[1;8;15;0;0;0;0;0][7;9;0;0;0;0;0;0][11;13;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][10;14;12;6;3;5;4;2][0;0;0;0;0;0;0;0]	23	90	144	12	78	0
11	[1;8;15;0;0;0;0;0][9;13;0;0;0;0;0;0][7;11;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][12;10;14;6;3;5;4;2][0;0;0;0;0;0;0;0]	24	90	144	12	78	0
12	[1;8;15;0;0;0;0;0][9;13;0;0;0;0;0;0][7;11;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0][14;10;12;6;3;5;4;2][0;0;0;0;0;0;0;0]	14	90	144	12	78	0
13	[1;8;15;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][9;7;11;5;2;0;0][12;13;14;10;6;3;4][0;0;0;0;0;0;0]	9	90	144	12	78	18
14	[1;8;15;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][5;0;0;0;0;0;0][13;7;11;6;3;4;2][14;12;9;10;0;0;0][0;0;0;0;0;0;0]	2	112	2601	51	61	601
15	[1;8;15;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][6;0;0;0;0;0;0][0;0;0;0;0;0;0][9;11;7;3;5;4;2][13;14;12;10;0;0;0][0;0;0;0;0;0;0]	4	110	3249	57	53	549
16	[1;8;15;0;0;0;0][11;6;0;0;0;0;0][13;9;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][7;0;0;0;0;0;0][10;14;12;3;5;4;2][0;0;0;0;0;0;0]	16	155	30976	176	-21	1774

17	[1;8;15;0;0;0;0][13;6;0;0;0;0;0][9;7;11;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][14;12;10;3;5;4;2][0;0;0;0;0;0;0]	10	155	30976	176	-21	1769
18	[1;8;15;0;0;0;0][7;13;6;0;0;0;0][9;11;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][14;10;12;3;5;4;2][0;0;0;0;0;0;0]	19	157	31329	177	-20	1805
19	[1;8;15;0;0;0;0][7;9;6;0;0;0;0][13;11;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][12;10;14;3;5;4;2][0;0;0;0;0;0;0]	13	156	31329	177	-21	1802
20	[1;8;15;0;0;0;0][9;0;0;0;0;0;0][7;13;11;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][6;0;0;0;0;0;0][0;0;0;0;0;0;0][12;10;14;3;5;4;2][0;0;0;0;0;0;0]	22	144	18496	136	8	1476
21	[1;8;15;0;0;0;0][9;13;0;0;0;0;0][7;11;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][0;0;0;0;0;0;0][14;10;12;3;5;4;2][6;0;0;0;0;0;0]	25	96	729	27	69	162
22	[1;8;15;0;0;0][0;0;0;0;0;0][0;0;0;0;0;0][0;0;0;0;0;0][0;0;0;0;0;0][0;0;0;0;0;0][13;9;7;6;4;2][11;12;14;10;3;5][0;0;0;0;0;0]	8	95	484	22	73	141
23	[1;8;15;0;0;0][7;9;0;0;0;0][11;13;2;0;0;0][0;0;0;0;0;0][0;0;0;0;0;0][0;0;0;0;0;0][3;0;0;0;0;0][14;12;10;6;5;4][0;0;0;0;0;0]	27	90	144	12	78	0
24	[1;8;15;0][11;9;0;0][7;13;3;2][0;0;0;0][0;0;0;0][0;0;0;0][6;5;4;0][14;12;10;0][0;0;0;0]	17	95	441	21	74	146
25	[1;8;15;0][3;0;0;0][0;0;0;0][0;0;0;0][6;0;0;0][5;4;0;0][11;13;7;2][9;10;12;14][0;0;0;0]	1	339	134689	367	-28	6740
26	[1;8;15;0][7;13;9;0][11;6;0;0][0;0;0;0][0;0;0;0][0;0;0;0][3;5;2;0][10;12;14;4][0;0;0;0]	18	91	169	13	78	26
27	[1;8;4;15][7;0;0;0][9;13;11;3][0;0;0;0][0;0;0;0][0;0;0;0][6;2;0;0][14;12;10;5][0;0;0;0]	26	125	10201	101	24	955

Other strategies like strategies 13 and 26 only have a very small absolute regret, but therefore would not be recommended to the decision maker at this stage. The best deconstruction strategy in the worst-case scenario is strategy 23 with an average $C_{max} = 90$ and an absolute regret $AR(\Pi(z_k)) = 0$. As the absolute regret of the optimum strategy of worst case scenario is zero, the explicit hedging against the worst case it is not recommended to the risk-neutral decision maker. However, a risk-averse decision maker would prefer strategy 23 as it includes the optimum schedule in the worst case (scenario 27).

The data in Table 5—11 is visualized in Figure 5-20 and Figure 5-21 with a predefined maximum limit of the y-axis for a better clarity of the model results. Figure 5-20 shows the unsorted deconstruction strategies and their robustness criteria values after the stress test of the strategies on all scenarios. Figure 5-21 shows the sorted deconstruction strategies according to their absolute regret value sorted in ascending order.

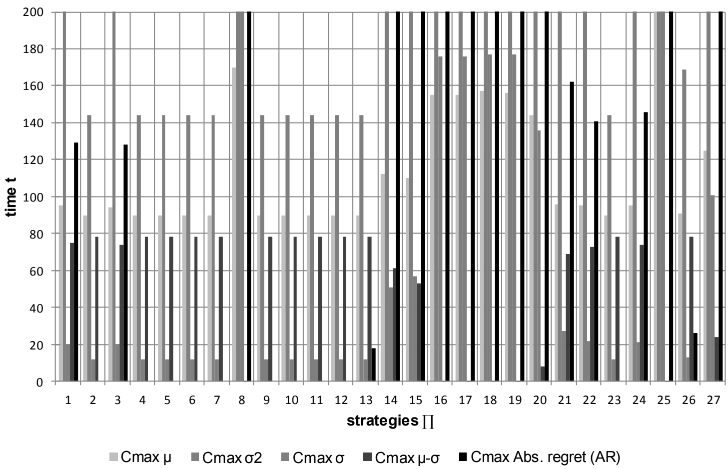

Figure 5-20: Visualization of the identified deconstruction strategies and their robustness measures (absolute regret: black) of case study 1 after the stress test on all scenarios, in ascending order of the strategy IDs

In both figures, the most robust strategies with average absolute regret (black bars) AR=0 can be seen in Figure 5-21. Also, the other six strategies with comparably low average absolute regret values below 200 [time units] are visible, that also might become interesting deconstruction strategies in the case of information updates and a local search for robust and feasible deconstruction strategies under new information and conditions (see section 5.1.5).

Figure 5-21 shows the sorted average project makespan of all deconstruction strategies. In case study 1, it becomes obvious about two-thirds of the possible deconstruction strategies obtain a relatively low average project makespan, while the project makespan of the remaining third of the deconstruction strategies have considerably higher average project makespans. In Figure 5-22 the distribution of average project cost and average project makespan for all strategies over all scenarios are represented. Here, often a linear relation between project time and project cost is assumed in literature which is represented and in this case confirmed by the linear trend line for the deconstruction project in case study 1. The numbers in Figure 5-22 label the respective numbers of the deconstruction strategies.

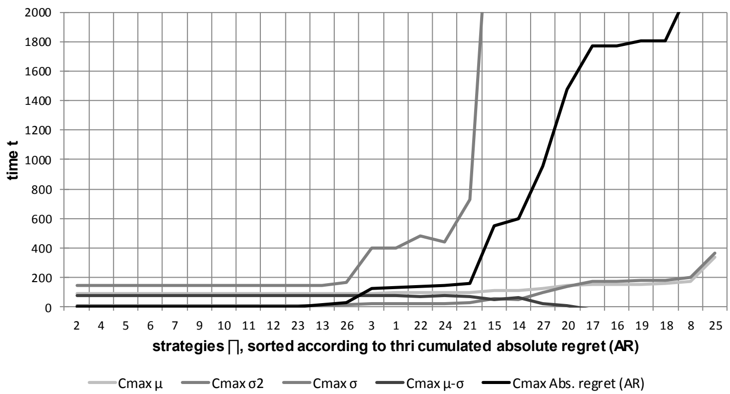

Figure 5-21: Visualization of the identified deconstruction strategies and their robustness measures of case study 1, in ascending order according to the deconstruction strategies' average absolute regret values (black), and the related mean µ and standard deviation σ robustness criteria values

To compare the optimal solutions (deconstruction strategies) with zero average absolute regret with each other and to recommend the 'best' deconstruction strategy to the decision maker, several possibilities exist. Either average project makespan or average cost of the deconstruction strategies with zero absolute regret are compared. Or, both values are considered, e.g. in multi-criteria methods and a respective weighting of the two objectives is necessary. Here, first the deconstruction strategy with minimum average project makespan is selected. If there is more than one deconstruction strategy with a zero absolute regret and the minimum average project makespan, then the deconstruction strategy with the minimum project costs is selected. Thus, the closest strategy to the point of origin is regarded as the ‘best’ solution. In case study 1, according to this procedure deconstruction strategy 2 is recommended to the decision maker. The “next best” (nearest to the “best”) solution from the viewpoint of the risk averse decision maker can be determined with an appropriate distance metric.

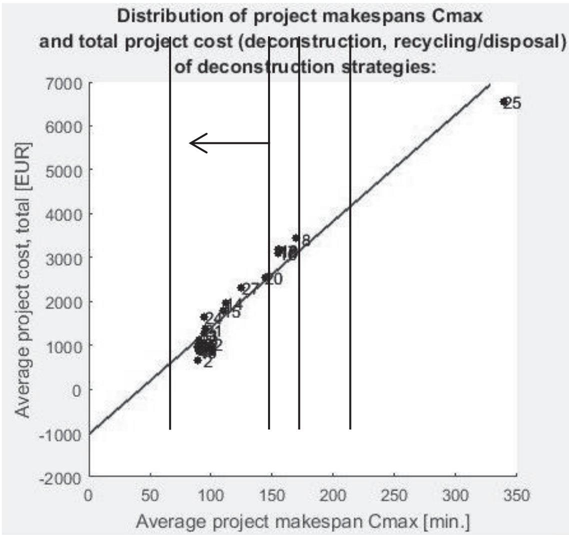

Figure 5-22: Distribution of average project makespan and average project cost of all deconstruction strategies over all scenarios in case study 1

In the baseline scenario 14 that can be seen as the deterministic case, deconstruction strategy 12 is chosen as the optimal strategy. Strategy 12 has an absolute regret of zero and belongs to the set of optimum strategies that could be recommended to the decision maker. However, considering the robustness analysis and the resulting total project cost, strategy 2 proved to be equally robust strategy with a lower average total project cost over all scenarios.

5.1.5 Part D: Information updates and project changes

In the fictive case study 1, only hypothetic information updates can be assumed to show the mechanism of the developed model that is described in section 4.6 and visualized in Figure 4-15.

In model part C of case study 1 (section 5.1.4), the optimum strategy 2 is recommended to the decision maker. In the case of new information and strategy feasibility, only the deconstruction schedule is adapted via right-shift if necessary. This case is not further considered here. In the case of schedule infeasibility, e.g. due to new information, another deconstruction strategy is either identified by local search, or generated by rescheduling (reuse of the proposed model). For example, if in case study 1 the new information arises after project start, that activity 7 cannot be performed in mode 8, e.g. because of a resource unavailability or another material than previously assumed and a resulting unsuitability of the originally planned deconstruction technique. If activity 7 cannot be performed in mode 8 but only in mode 3, a local search could identify still feasible deconstruction strategies in the list shown in Table 5-11. Here, for example strategies $\Pi = \{4,5,6,7,11,12,17,20,21,24\}$ would still be possible and strategies $\Pi = \{4,5,6,7,11,12\}$ would also have an absolute regret of zero. Strategies $\Pi = \{17,20,21,24\}$ would not be selected in this stage, as they induce a higher absolute regret value. However, in later stages, these strategies might be interesting alternatives, depending on a threshold value of the robustness criterion AR and the decision makers risk preference. A reasonably good objective value can be defined here for demonstration purposes with less than 5% deviation from the average objective value of the best strategy.

For strategies $\Pi = \{2, 4, 5, 6, 7, 9, 10, 11, 12, 23\}$ with a regret of zero, the average project makespan is 90 time units. Then, a deviation from the average objective value by 5% would lead to a maximum of 4.5 time units per scenario, which leads to 121.5 time units in 27 scenarios. Then, strategies $\Pi = \{21,24\}$ would be closely above the threshold value but still not be included into the set of recommended deconstruction strategies. This deviation threshold value of 5% can be found in (Scholl 2001 p. 149) but might be adapted to any other value depending on the risk preference of the decision maker.

In this new set of optimal and feasible deconstruction strategies $\Pi = \{4,5,6,7,11,12\}$ where activity 7 can only be performed in mode 3, the strategy with the minimum average project makespan and minimum average project cost can be selected. Here, all strategies have the same average project cost of $C_{max} = 90$, but strategies $\Pi = \{6,11,12\}$ have the lower average project cost of $C_{total} = 960$ EUR. Thus, the schedule is adapted to one of the new strategies.

However, if one of the strategies $\Pi = \{4,5,6,7,11,12,17,20,21,24\}$ is applied, activities 9, 11 and/or 13 are processed in mode 2 instead of mode 7 (in strategy 2). This shift of resource assignments and its effects needs to be considered in the local search. Also, if several information updates occur, the local search might be more difficult, or might not find a deconstruction strategy that is already listed and evaluated. Then, a rescheduling with the remaining building elements and the new information on resource availabilities, building element materials, deconstruction costs and durations has to be performed (see section 4.6.3).

5.1.6 Verification and sensitivity analysis

To verify case study 1, there are several possibilities. This section verifies the model results via a plausibility check, if the calculated values are in a realistic material mass and project cost range and provides a sensitivity analysis to demonstrate the effects of varying model and data parameters on model results.

Practitioners report deconstruction costs of a single family residential building that was built around 1960 with a gross volume of 600m³ at about 9600-10000 EUR. This includes considerable operating space around the building site and the recycling revenues from metal selling. Case study 1 only considers a single apartment with a gross volume of 240 m³. The calculated model results range from 1000-6000 EUR of total project costs, where the majority of cases and strategies range between 1000-3500 EUR. If these figures are compared based on the gross volume of 240 m³, then practitioners estimate the deconstruction cost for case study 1 in a range between 3840-4000 EUR. Assuming additional effort for other building elements that where not considered here, such as other technical equipment, the roof or the foundations of a whole building, the model results seem plausible.

The building inventorying part in model part A can be verified by the currently used estimation method of building material masses in practice. This building auditing method is based on the multiplication of material mass estimation factors by the gross volume of the designated structure. The method is described in section 2.3.1. and the respective estimation factors are listed in Table 2-6.

Table 5-12: Material mass estimations [t] for case study 1 based on gross volume estimation and on generic estimation factors[10]

Building / construction type	[t]	Before 1918	1919-1948	1949-today
Building type I, II (solid construction, masonry and reinforced concrete/timber))	Brick	51.36	53.76	49.44
	Timber	1.92	2.16	1.92
	Metals	1.68	1.44	0.72
	Other	0.72	1.44	4.32

In case study 1, a gross volume of 240 m³ is calculated for the four-room apartment. The apartment is constructed with masonry walls and timber slabs, and thus falls into the building or construction type II in Table 2-6[11]. As no information on the building age is available, all literature values on material masses are calculated for the three periods of construction to get a range of plausible values. The resulting material masses based on estimation factors and gross volume are compared with the

[10] According to (LfU 2001; Lippok and Korth 2007 p. 120) (see also Table 2-6 for different material categories).

[11] For material estimation factors per building gross volume of non-residential buildings see (Gruhler and Böhm 2011) or the verification section of case study 2 (section 5.2.5).

model-based building inventory values of case study 1 in Table 5-12 and are shown in Figure 5-23.

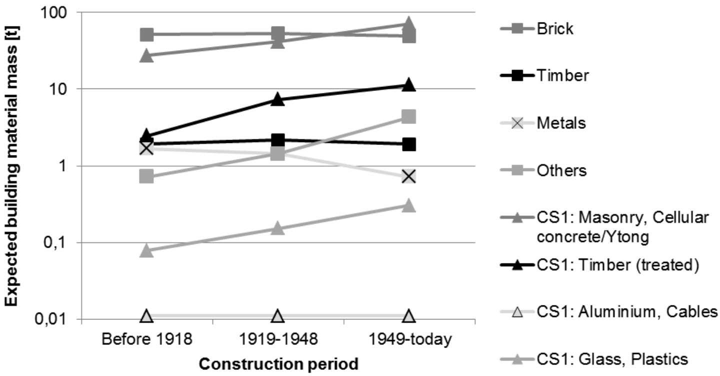

Figure 5-23: Comparison of building mass estimations [t] of gross volume estimation (squares) and model-based estimation for case study 1 (triangles represent minimum, expected and maximum values that are not related to periods of construction (x-axis))

The isochromatic lines in Figure 5-23 represent same material categories, while the squares show the gross volume-based estimation and the triangles show the model-based and construction period independent estimations. In Figure 5-23, it can be seen that some isochromatic lines lie closely to each other, while others are quite apart. In the case of brick and masonry, the model calculated between 27 t and 71 t, while the gross volume estimation has a far smaller range between 49 t and 54 t. But, the expected masonry mass of the model of 41 t lies very close to the verification range, especially if it is taken into account that only a single apartment is considered and inventorying parameters might not have been well-defined. For example, in the current model, small deviations result from the mass calculation of the walls due to the negligence of wall corners with adjoining rooms (see also section 4.3.2). Furthermore, brick is assumed to be the main wall material in the building type based estimation, whereas in the model cellular concrete is considered as wall material, which might differ in material densities (brick: 850-1900 kg/m³, cellular concrete bricks: 800-1800 kg/m³) and might lead to mass deviations. In the model, the following material densities are used for brick (1375 kg/m³) and cellular concrete bricks (1300 kg/m³).

The model estimation for timber between 2.5 t and 11.4 t is rather high. But, this might result from the fact, that in the model timber slabs are assumed to be solid slabs due to a simplified mass calculated in the case of timber slabs. In reality however, often 'false' ceilings (timber beams with considerable cavities) are used where their cavities are either empty of filled with insulation material e.g. against sounds, or thermal losses.

The estimation of metals (here: aluminum appliances in the electrical equipment and cables) is rather low. This can be explained by the rather low technical equipment assumed in this case study for simplicity. For example, here only electrical equipment is considered in a very low amount of installation points. Usually, the number of electrical outlets and lamps is higher, and drinking water, waste water and heating equipment further increase the metal masses in a building.

The other building material masses are also rather low estimated by the model in comparison to the estimation based on gross volume. Similarly, in case study 1 the amount of modeled interior fittings is rather low, e.g. additional floor covering or insulation material is not considered. In a more detailed case, this value will probably be higher. Also, a comparison of the model results with single well-documented selective deconstruction projects in literature is theoretically possible, e.g. with cases mentioned in (Görg 1997; Lippok and Korth 2007; Rentz et al. 1994b, 1998b; Seemann 2003). For example, the Hotel Post in Dobel (Lippok and Korth 2007 p. 432; Rentz et al. 1994b), constructed in 1910, was a timber-frame building with fillings, which does not exactly fit to the calculated case study but is one of the rare well-documented deconstruction projects based on a building with timber slabs. Perceived material masses from Hotel Post were transferred and material masses for the 240 m³ of the case study were calculated. Then, 44.88 t mineral material, 5.52 t timber, 0.72 t metals and 3.02 t of other materials would have been generated. However, the well documented exemplary single cases of deconstruction projects and their respective material estimation factors in literature are often not transferable to other buildings and thus not valid for benchmarking.

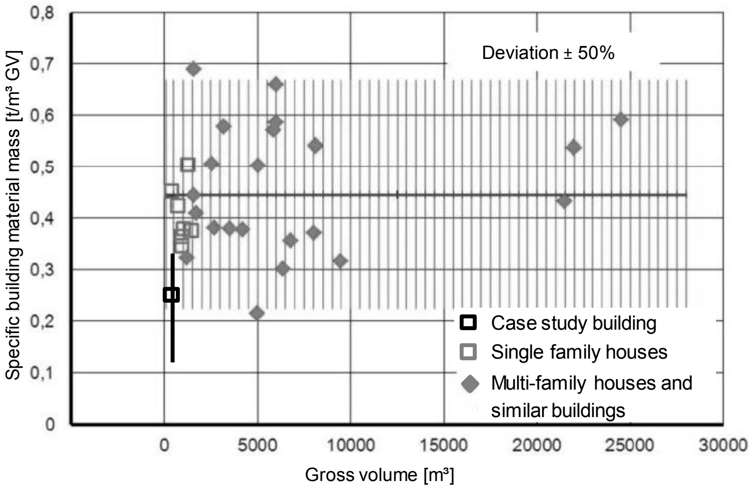

Figure 5-24: Relation between buildings' gross volume (x-axis) and its specific mass in t/m³ of the gross volume (y-axis) for residential buildings[12]

Figure 5-24 shows the specific building mass [t/m³ GV] (y-axis) of single-family (square) and multi-family (rhombus) residential buildings in relation to the buildings gross volume [m³] (x-axis) with a ±60% deviation range (shaded area). Compared to the data displayed in Figure 5-24 for residential buildings, in case study 1 a range of the specific building mass ratio [t/m³ GV] of 0.125 – 0.3458 is calculated by the model and is shown in Figure 5-24 by the vertical black line. The expected value lies at 0.2041

[12] According to (Müller 2013 p. 5f.), (accessed: 19.05.2016).

and is displayed with a small black square. It can be seen, that the specific mass value of case study 1 is rather low, compared to other single and multi-family residential houses. This might be caused by the consideration of a single apartment and not a whole building with roof and foundations that might increase the specific mass.

As discussed in sections 4.7.2 and 6.2, uncertainties in the data are possible that are based on uncertain documentation, uncertain spatial building information, and assumptions on model parameters or building parameters. As often as possible, possible parameter ranges are used in the model to demonstrate the minimum, expected and maximum values.
Considerations regarding the sensitivity of the model results are described in the following. Sensitivity analysis is defined as the examination of the influence and the impact of minor variations or deviations of single input parameters on the objective value (Nickel et al. 2014 p. 61) or on the model outcome (Girmscheid and Busch 2014 p. 124; Munier 2014 p. 16). Sensitivity analysis is a post-solution analysis that tries to answer several “what-if” questions on the optimality of the generated schedule that arise from input parameter changes (Gören and Sabuncuoglu 2008 p. 67; Herroelen and Leus 2004 p. 1612). A sensitivity analysis can be described as an indirect method of uncertainty consideration (Scholl 2001 p. 189). It is characterized by the systematic variation of model input parameters in a post-optimal analysis that is varying parameter values’ percentally over a defined range of the parameter value. The aim of sensitivity analyses are to identify the limits to the change of a parameter so that the solution remains optimal and it answers the question what the new optimal solution or costs are given a specific change of a parameter (Herroelen and Leus 2004 p. 1612). For that purpose, input data and parameters are calculated with their expected values and then varied in percental increase/decrease (Bertsch 2008; Girmscheid and Busch 2014 p. 124; Merz 2011 p. 148). Variation can either be performed via distribution information and Monte Carlo

simulation or manually selecting the most relevant or protruding (minimum value, expected value and maximum value) values (Merz 2011 p. 149). Due to the large number of distributions, it could be difficult or cumbersome to select adequate distributions, and results may differ greatly when a problem is solved using different distributions (Munier 2014 p. 10). However, some researcher affirm that examination of many Monte Carlo analyses show that results do not differ largely (Munier 2014 p. 10). The results of sensitivity analyses are shown in a sensitivity diagram and demonstrate the sensitivity of the model results to parameter changes.

However, for integer linear optimization problems and especially for binary optimization problems the possibilities of a sensitivity analysis are limited due to structural differences of the solutions (Scholl 2001 p. 189f.). According to Scholl (2001), often only different parameter constellations (also called scenarios) can be used to obtain useful results of the sensitivity analysis.

In this model, a binary optimization problem is solved for every scenario. Thus, a classical sensitivity analysis with a percental variation of model input parameters over a value range is not reasonable. Rather, different parameter constellations can be calculated by the model and the model results can be compared with each other. In this research approach, this uncertainty consideration via scenarios is explicitly done by the proposed scenario construction (see section 4.3.6) and the following evaluation of the optimization model results (sections 4.4 and 4.5).

However, as decision makers risk preferences and preference parameters are subjective (Belton and Vickers 1990; Bertsch 2008 p. 22), the effect of differing risk preferences can be evaluated in a sensitivity analysis. In the proposed decision making case of deconstruction project planning, risk-averse decision makers are in the focus. However, their degree of risk aversion is not differentiated by the model yet. To analyze the degree of risk aversion the Hurwicz robustness criterion can be used, to show the effects of the risk preference graduations between risk neutrality and risk aversion on deconstruction strategy selection. The

Hurwicz criterion maximizes or minimizes the linear combination of the minimum and maximum objective value of an alternative with an optimism parameter $\lambda \in [0; 1]$ (Scholl 2001 p. 136f.). If $\lambda = 0$, the decision maker is assumed to be very pessimistic (=mini-max criterion) and if $\lambda = 1$ the decision maker is very optimistic (=maxi-max criterion) (see also section 3.2.4).

Figure 5-25 depicts all 27 deconstruction strategies and the change of their objective value (project makespan) in relation to their degree of risk aversion. The lines in Figure 5-25 show, that there are some deconstruction strategies, that are stronger affected by the different risk preferences of decision makers, such as strategies $\Pi = \{8,16,17,18, 19,20,25\}$ which is reflected by a relatively steep gradient, while others like $\Pi = \{2,4,5,6,7,10,11,12,13,23,26\}$ are not or less influenced. The not influenced strategies are dominant strategies and have an absolute regret of zero.

Similarly, the Hodges-Lehmann criterion applies a confidence parameter $q \in [0; 1]$ (Scholl 2001 p. 129) and combines the expectancy value μ over all scenarios with the pessimistic mini-max criterion, respectively the most unfavorable objective value. It is shown in Figure 5-26 that in this case deconstruction strategies $\Pi = \{8,16,17,18, 19,25\}$ are very sensible to variances of the risk preferences, while others like $\Pi = \{2,4,5,6,7,10,11,12,13,23,26\}$ are less or not sensible.

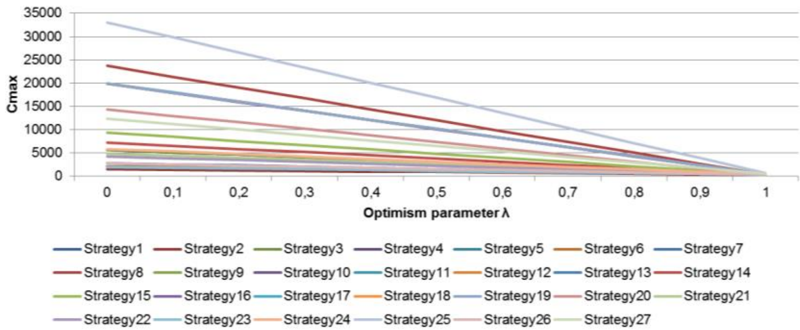

Figure 5-25: Robustness evaluation based on Hurwicz criterion with optimism parameter λ for case study 1

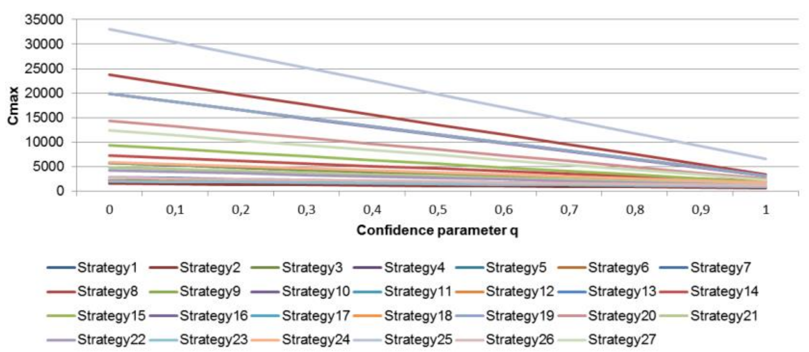

Figure 5-26: Robustness evaluation based on Hodges-Lehmann criterion with confidence parameter q for case study 1

5.2 Case Study 2: Hospital St. Georg, Bad Pyrmont (non-residential building)

This section describes the exemplary model application for the deconstruction project planning of a part of a hospital in Bad Pyrmont that was audited in July 2015 and subsequently deconstructed by industry partners in a research project. The case study building is a former hospital that was not used for about 6 years with three to five floors and a full basement. Figure 5-27 shows the center wing with patient rooms on four floors from the yard (left) and from the road (right). Figure 5-28 depicts the emergency plan of the second floor, and shows the floor plan of the hospital. The case study addresses a part of a hospital, which belongs to the class of non-residential buildings of the healthcare sector. Thus, it belongs to the group of "complex" buildings (Domingo 2015 p. 860). Due to their unique functional and operational features, hospitals often have complex and branched floor plans and have ramified technical equipment of several types such as water, waste water and power lines, but also oxygen pipes, communication and emergency systems or air conditioning. Thus, the building auditing and the deconstruction planning including the capture of building information such as building element mass, time, cost and waste estimations of such complex buildings and structures are challenging for these building types.

Section 5.2.1 describes the whole data set of case study 2 that is used for the deconstruction project planning and the model application. Section 5.2.2 shows the inventory results of the model and the scenario construction based on the building inventory. Section 5.2.3 provides the reader with the scheduling results for case study 2. Section 5.2.4 describe the model results for the robustness evaluation of the generated deconstruction strategies in this case study. Section 5.2.5 concludes with verification and sensitivity analyses of the generated model results.

Figure 5-27: Exterior view on the case study building hospital St. Georg (left: view from the yard, right: view from the road)

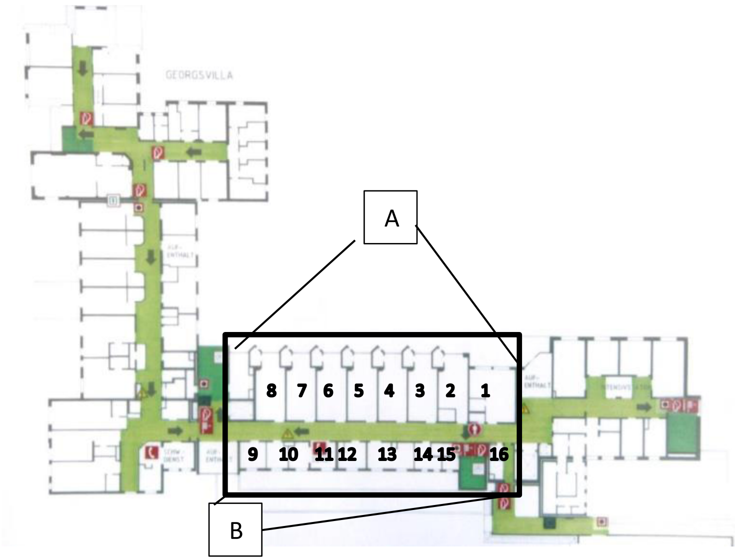

Figure 5-28: Floor plan of assessed 2nd floor in hospital St. Georg, Bad Pyrmont, with designated assessment area (black frame) and main room numbers as well as the exterior viewpoints of Figure 5-27

Figure 5-29 shows several interior views into the central aisle, the former patient rooms, baths and treatment rooms. In Figure 5-29 (tile 2) the application of the ResourceApp sensor system (see also section 4.3.2) can be seen in a (partly destroyed) patient room in the building interior. Here, the state of the building can be seen with several destroyed building elements, furniture from former building use and other disturbing factors for the automated capture of building information. During the automated and the manual assessment, all 30 rooms (including the central aisle) were captured.

5.2.1 Description of the building and used data sets

In the deconstruction project planning model, several project-specific and general data sets are applied to calculate building inventory, building element surfaces, volume and masses as well as durations and cost of deconstruction activities. Sources of project specific data are onsite measurements (via CSV/OBJ) (also described in section 4.3.2) and user inputs. Sources of general building and building element data are standards (DIN, ISO), literature and expert estimations. This subsection gives an overview on the applied data sets in this case study.

Case study 2 constitutes a hospital story with 30 rooms that can be seen in Figure 5-29. All rooms were automatically captured as described in section 4.3.2 and the relevant information was provided in the CSV/OBJ data interface as model input. Exemplary, Figure 5-30 shows indoor photographs of a single patient room of the test building. In the upper left tile in Figure 5-30, the original patient room can be seen. In the upper right tile in Figure 5-30, the reconstruction point cloud of the same room can be seen, where some building elements are easily recognizable such as the door, window and radiator. On the lower right tile in Figure 5-30, there is the fully reconstructed patient room visible (from the other side). On the lower left tile in Figure 5-30, the automated building auditing can be seen with the optical sensor that is capturing room and building element information.

Figure 5-29: Interior view of case study building hospital St. Georg, Bad Pyrmont, 2nd floor (1: Aisle, 2: patient room (room no. 1), 3: bathing and treatment room (room no. 12), 4-5: patient rooms (room no. 3-8) with separate bath room (6)

The verification of the dataset that graphically describes and models the hospital story in Autodesk Revit[13] (see also upper part in Figure 5-33) is based on manual measurements by laser distance meter of all inherent building elements. The measurements were done by the author during two site inspections in summer 2015. Figure 5-31 and Figure 5-33 show the automatically and manually captured data sets graphically.

[13] Autodesk Revit is the most widely used building modeling software in the US (Becerik-Gerber and Rice 2010).

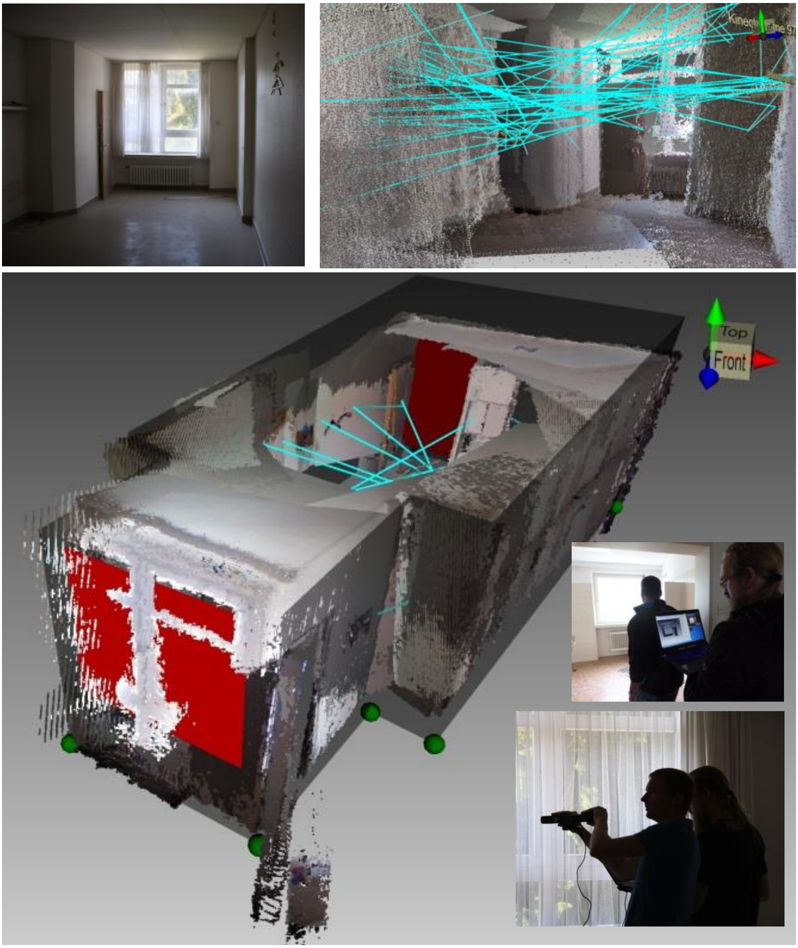

Figure 5-30: Interior patient room, top and bottom: point cloud and 3D reconstruction (Fraunhofer IGD), top right: photograph of the patient room reconstructed in images left, bottom right: 3D sensor users in a patient room

Table 5-13: Numbers of automatically recognized vertices, faces and building elements (from CSV interface)

General information	Structural building elements	Fitting building elements
26 Rooms 295 Building elements 564 Vertices 269 Faces	26 Ceilings, 26 Floors 165 Walls	19 Windows 24 Doors 9 Radiators 26 Sockets and switches
	217 Structural building elements	**78 Fitting building elements**

Table 5-14: Numbers of manually captured vertices, faces and building elements

General information	Structural building elements	Fitting building elements
30 Rooms 512 Building elements 1550 Vertices 316 Faces	30 Ceilings, 30 Floors 165 Walls	26 Windows 29 Doors 36 Radiators 107 Sockets, 44 Switches and 19 Emergency switches 11 WC, 11 Washbasins, 3 Shower, 1 Bathtub
	225 Structural building elements	**287 Fitting building elements**

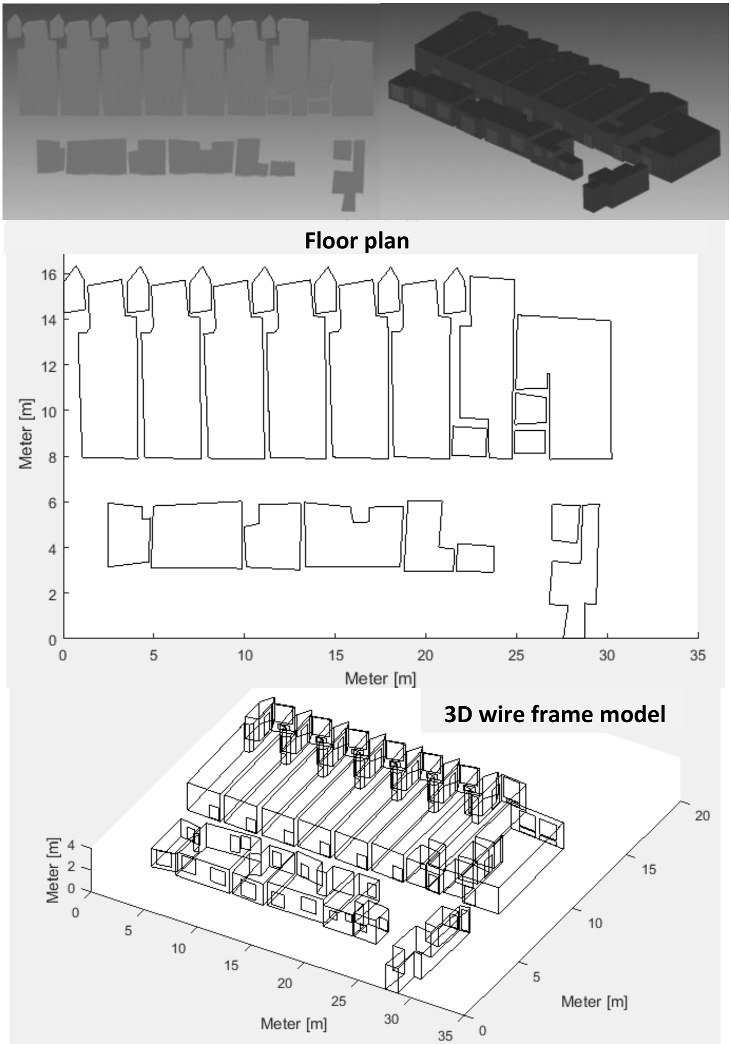

Figure 5-31: Case study 2 with floor plan and reconstructed 3D model based on sensor data in the processing tool (top) and in the developed model (bottom) (center: floor plan; bottom: 3D view in isometric projection[14])

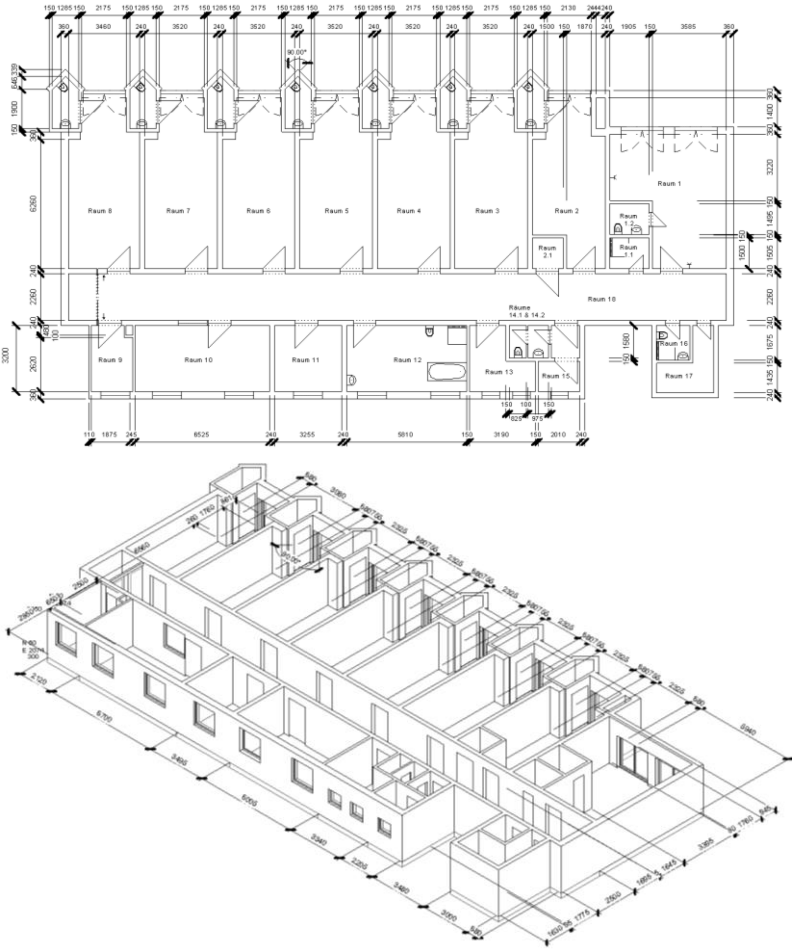

Figure 5-32: Case study 2 (2. floor of hospital) with modeled floor plan based on manually audited building elements represented in Autodesk Revit (top: floor plan; bottom: 3D view in isometric projection[14])

[14] Isometric projection is a usual depiction of buildings with α=β=30°.

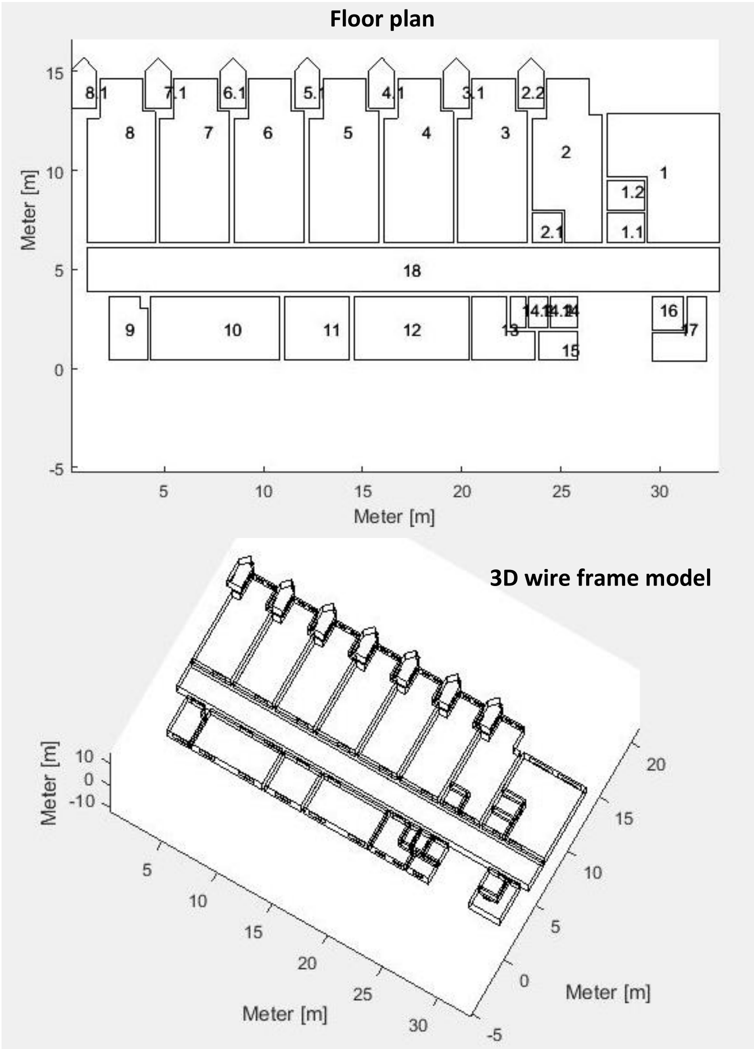

Figure 5-33: Case study 2 (2. floor of hospital) with modeled floor plan and reconstructed 3D model based on manually audited building elements represented in the developed model (top: floor plan; bottom: 3D view in isometric projection[14])

Automatically recognized building elements by the sensor and sensor processing software were walls, floor, ceiling, windows, doors and electrical outlets. Manually, further building elements were audited such as TEQ drinking water, TEQ waste water, TEQ heating and TEQ IT emergency. The data set of indoor building information capture in the CSV-interface and OBJ-interface of the examined hospital level (2.OG) include the following numbers of vertices, faces and building elements that are aggregated in Table 5-13 and Table 5-14. Both tables differ in the amount of automatically recognized building elements and the real number of building elements.

As can be seen in Figure 5-31, Figure 5-32 and Figure 5-33, patient rooms have octagonal floor areas (in reality even with nine corners and nodes) and most of their bathrooms are pentagonal (above the aisle). Consulting and treatment rooms as well as staff rooms below the aisle are rectangular rooms, mostly with quadratic shape. Main differences between automatically and manually captured data sets in Table 5-13 and Table 5-14 are two small undetected bathrooms and the main aisle. The bathrooms could not be detected due to their small floor area and the required minimum distance between sensor and walls and the aisle detection was problematic due to its uniformity and elongated shape that was difficult to detect by the sensor.

During the second building site inspection, a floor plan of the second floor was found in the hospital cellar. Then, implausible or missing measurements were complemented by information from the floor plan of the 2nd floor. However, although the found floor plan was not accurate in all details (not as-built), main structures of the building were sufficiently good described. The complementation by this secondary information source was especially useful in the distances modeling between the room doors in the aisle, because the aisle and its building elements were not easy to measure due to their length. Further necessary information such as the room or building element height is either derived from the data set or based on standards.

During the site inspection, the user can enter the basic material information of the building elements. For example, in case study 2, based on the CSV-interface information the model imports the plastered brick walls on the whole story and PVC covered floors in all patient rooms (1-8). As this building is located in a water protection area, several reports on building materials, layers, contaminations and hydro-geological information were conducted and provided by the industrial project partners. Thus, information on building element materials was available. The considered part was free of hazardous materials.

Beyond the interface data from CSV/OBJ files, the proposed model requires user input on several general and project-specific building information of the deconstruction project. For that purpose, the model user can enter data such as building name, address, community and state as well as building type[15], construction type, year/period of construction, number of stories, roof style, foundation style and the building size (gross volume, gross area) into an user interface (see Figure 5-34). This data is mainly collected for later project documentation, except for the construction type and the foundation style which are used in the subsequent inventory calculations. The hospital story in question can be assigned to the construction type Ia (according to Figure 2-5) that consists of a solid building construction with masonry walls and reinforced concrete slabs. The roof style is not used here, as both case studies are building stories where no roof is considered.

As can be seen in the graphical user interface displayed in Figure 5-34 (left part), the following information on the example case study 2 are known from building documentation and the fictive apartment is classified as:

[15] Information based on standards for residential, non-residential, and health care buildings (or similarly constructed buildings) are available in the model. Standards' information regarding other building or construction types have to be added to the model if required.

- ‘Bauwerksuntergruppe’ (building subgroup) = ‘Nicht-Wohngebäude’ (non-residential building),
- ‘Bauwerksklasse’ (building class) = ’Anstaltsgebäude’ (institutional building),
- ‘Bauwerksunterklasse’ (building subclass) = ’Krankenhäuser’ (Hospitals) and
- ‘Gebäudetyp’ (construction type) = ‘I: Massivbau: Mauerwerkwand – Stahlbetondecke’ (masonry with reinforced concrete ceiling).

A building age is not known. However, the found floor plan is dated from 1989, but it is unsure if the planned measures where new construction or retrofitting of the building wing in question and thus the respective data field is left empty. There is just a single story considered, including eight combinations of patient rooms with attached bathrooms and a staff kitchen but no apartment units. Thus, this field is left empty.
As this case study only includes a single story, a cellar is not assumed and instead of a foundation the floor[16] is assumed to be a standard reinforced concrete slab like the ceiling. The ceiling is assumed to be a reinforced concrete slab, which is based on the construction type Ia information that was entered by the user. The roof style is considered a flat roof although further calculations on the ceiling or roof covering from above are not made here. A gross volume or gross area information is not known.
In the center part of the graphical user interface in Figure 5-34, information on the technical equipment’s’ characteristics and connection points to public supply lines can be entered for the apartment or building. In case study 2, technical equipment (TEQ) of power, drinking water and waste water is considered. The main story and building power port are given in the CSV/OBJ data at (x = 4.00; y = 4.00; z = 1.00) in the coordinate system with the parent wall ID = 272, which is located in the

[16] In the case of a base plate or foundation slab, a floor slab with a protrusion of twice the wall thickness would be assumed.

aisle. Similarly, main story and building ports for waste water (WWATER) and drinking water (DWATER) are located in the aisle on parent wall ID =272. The waste water port is assumed to have the coordinates at (x = 34.00, y = 4.00, z = 0) and the drinking water port is assumed to lie at (x = 34.00, y = 4.00, z = 1.00). As described in the respective construction norms, the drinking water ports are always located at least 0.2 m away from the waste water pipes, are not allowed to cross waste water pipes and should lie above the waste water ports (DIN 1988-100:2011-08, DIN EN 806-2:2005-06). If the technical equipment port information is not entered via the user interface, the ports might be recognized and transferred automatically via CSV/OBJ interface or the model assumes the origin of the coordinate system to be the central TEQ connection point.

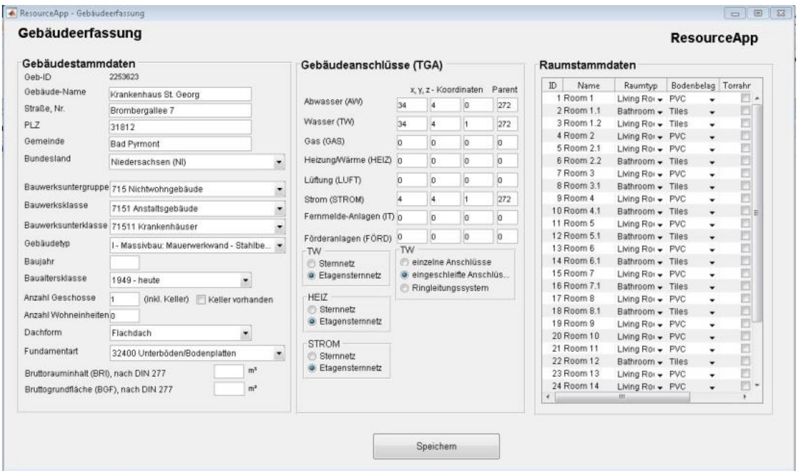

Figure 5-34: Graphical user interface for general building/project information with exemplary information on case study 2

The right part of Figure 5-34 shows a list of already imported rooms from the CVS/OBJ data set, their room type (if this can be determined via the recognized building elements) and their floor covering based on CSV interface information. For example, rooms 1.1, 1.2, 2.2, 3.1, 4.1, 5.1, etc. were already automatically recognized as bathrooms.

Further building information and parameters can be entered similarly via user interfaces or via Microsoft Excel interface. The kind of inventorying parameters and information that can be entered or varied in the second graphical user interface that is shown in Figure 5-5 (case study 1, section 5.1.1). In case study 1, the building element properties and parameters and their default values are explained in detail (section 5.1.1). The default information is dependent on the previously entered building type and based on extensive researches of German building and construction standards and related literature. In case study 2, the average material density values are considered. Also, standard frames width values of 0.04 m for windows and 0.06 m for doors are assumed. Furthermore, window and door wing thickness are assumed to be 0.04 m in both cases and the percentage of window and door wing frame is assumed to be 20%. In this case, 30% percentage of copper in usual electrical wiring was selected due to recommendation of practitioners' experiences. This constitutes a rather low value, as scrap merchants consider 38% as a standard value for the copper percentage in electrical wires.

Furthermore, case study 2 is a story in a hospital wing, with its ceiling and floor as slabs (no roof, no foundation), so that the half ceiling and floor thickness is calculated. If tiles or PVC are installed as floor covering, a layer of screed is automatically assumed by the model. However, the screed thickness cannot be directly modified by the user, but can be changed in the model itself, if necessary.

The reinforcement (in the case of reinforced concrete walls, ceilings or floors) can be selected either via percent values or via kg/m² visible building element surface. The reinforcement calculation with the latter value is the common way in practice for calculating the inherent steel quantities in reinforced concrete walls in deconstruction projects. Default values [kg/m²] for walls, slabs and foundation made of ready-mixed concrete stem from (Hauer 2010), but depend strongly on the originally planned loads and the room size (track width, field width of ceiling panels). For walls (load-bearing exterior cellar walls), reinforcement factors between 6.02 kg/m^2 and 10.42 kg/m^2 are proposed depending on the wall loads (for up to 300 kN/m and between 400 to 600 kN/m) (Hauer 2010 p. 6f.). For foundation and floor slabs (Hauer 2010 p. 6f.) propose reinforcement factors between 2.33 and 10.00 kg/m^2, depending on the wall loads and the span length[17]. However, due to expert information, the reinforcement default values for case study 2 were set to their experience values of 1 kg/m² for walls, ceiling, floor and foundation slabs, which might be a rather cautious estimation compared to literature values. Here, the reinforcement calculation for walls, ceilings, floors and foundations is done with a factor [kg/m²] which is multiplied by the respective visible foundation, floor or ceiling area. The considered parameters in this case study are shown in Table 5-15.

In future research, the reinforcement values for ceiling and foundation/floor slabs might be calculated room-wise in more detail, based on standard load and reinforcement calculations according to room sizes, room span lengths and effective loads and on structural analyses and reinforcement bar placements. And, wall reinforcement values might be adapted according to the level information and assumed loads of higher levels.

Table 5-15: List of inventorying parameters used in case study 2

Model parameters	**Unit**	**Model parameters**	**Unit**
Floor slab thickness	0.20 m	Window frame percentage	20%
Floor slab reinforcement	1 kg/m²	Window frame thickness	0.04 m
Wall thickness, exterior	0.24 m	Window glass thickness	0.01 m
Wall thickness, interior	0.115 m	Door frame percentage	20 %
Ceiling slab thickness	0.20 m	Door frame thickness	0.06 m
Ceiling slab reinforcement	1 kg/m²	Copper rate	30%

[17] For ceiling slabs the reinforcement factors vary between 3.67 and 10.42 kg/m^2.

Table 5-16: Renewable resource capacities in case study 2

ID	**Resources** (*: with hydraulic excavator)	**Resource availability case study 2**
1	Hydraulic excavator, 200kW	2
2	Dragline excavator, 220kW	1
3	Crane, hoist, 63tm, 2400kg	1
4	Attachment sorting grab*	2
5	Attachment demolition stick*	1
6	Attachment steel cable*	1
7	Attachment hydraulic hammer*	2
8	Attachment combi-cutter/scissors*	2
9	Attachment crusher*	1
10	Attachment steel mass	1
11	Hand-held electric hammer	3
12	Hand-held wire saw	1
13	Hand-held core drill	1
14	Hand-held flame cutter	1
15	Attachment cutting head*	1
16	Hand-held grinding machine	1
17	Water jet cutter	1
18	Swelling agents, explosives	1
19	Container	0
20	Staff – Machine operator	2
21	Staff – Normal Worker	8

Regarding the project-related data sets of minimum, expected and maximum deconstruction activity durations and cost parameters per building element and renewable resource, in case study 2 default values of the model are used (see section 5.1.1 for information on the data sources). This data is imported and presented to the model user in a third graphical user interface (see Figure 5-6). In this user interface, the user can change his resources to his actual set of machinery that is available for the project in question and determine their capacities that are available for the current deconstruction project. In this case, the capacities of the renewable resources are set to the values in Table 5-16. The resource availability and capacity is assumed to be constant over project makespan. Also, the rooms are listed here as renewable resources but their use is not associated with additional cost. The activity-mode-resource demand per deconstruction mode can be seen in Table 5-4 and were not changed in case study 2.

5.2.2 Part A: Building inventorying and scenario construction

In the first model result, the gross floor area and the gross volume of the hospital story data set is calculated. Figure 5-35 shows the gross floor area and Figure 5-36 depicts the gross volume for the hospital dataset of case study 2. This calculation is done automatically via a triangulation and the enveloping function (convhull) in MATLAB, as it is very difficult to manually define the calculation process that is considering every protrusion, recess and niche in the floor plan.

As can be seen in Figure 5-35 and in the left diagram of Figure 5-36, the corner points of the hospital rooms are enveloped by a red and a blue polygon. The red (inner) polygon indicates the gross floor area and gross volume calculated from the sensor data of the interior building elements. The blue (outer) polygon also includes the enveloping building elements, such as outer walls, ceiling and floor. As the sensor data is only collected from the building interior, the enveloping building elements are not considered in this gross floor and gross volume value. For case study 2, the external (blue) gross floor area (GFA_{ext}) and gross volume (GV_{ext}) is calculated with building element thicknesses that are inserted in graphical user interfaces. This includes especially the outer walls', ceiling slabs' and floor slabs' thickness. In the case study 2 for the hospital dataset, a $GFA\ = 477\ m^2$ based on the interior dimensions and a $GFA_{ext} = 500\ m^2$ for the exterior dimensions including the enveloping building elements is calculated. This results in a difference of 3.56%. The calculated gross volume is 1312 m³ or respective 1503 m³, when the exterior dimensions are considered. This results in a gross volume deviation of 12.71%.

In the right diagram of Figure 5-36, a Delaunay triangulation of the point cloud can be seen, that also generates the same gross volume. As there are niches, recesses and protrusions due to the pentagonal bathrooms, both calculations do not exactly calculate but only estimate the GFA and GV based on the CSV/OBJ data and the model parameters. And, in the model the calculation of the buildings' gross floor area and gross volume is rather estimation than the exact determination of this value as it is defined in DIN 277-1:2005-02 for architectural purposes.
Then, the building elements and materials are inventoried with their volumes and masses. As the detailed building element inventory includes more than 1100 rows, it is not presented here. Material-specific inventories and an aggregated inventory are calculated as well. The aggregated inventory is shown in Table 5-17 with minimum, expected and maximum masses. In the model, 29 material categories are differentiated, but the presented inventory in Table 5-17 is reduced to the occurring material fractions. The comparison of the calculated building masses in the model with the measured/verified material masses during project execution (right column of Table 5-17) shows that some values are closely together while others differ greatly. With the currently chosen parameters the model calculates rather to high concrete masses, which can be explained by a too large floor and ceiling slab thickness. Currently, a slab thickness of 0.2 m is assumed. When this value is reduced to 0.15 m, the model results range between 52326 kg and 224885 kg, where the verified value with 47781 kg lies closely to the lower bound of the interval. The same applies for the brick masses of the exterior and interior walls. The developed model calculated with a thickness of 0.24 m (exterior) and 0.115 m (interior), which might be too high in the case of the exterior wall thickness. Also, in the model the material volume is multiplied with a brick density of 1375 kg/m³. However, in the case study building, perforated bricks were installed with a density of about 600-650 kg/m³. The multiplication of the material volume with the corrected density would lead to a range of 75535 – 141230 kg which might be further reduced by a reduced wall thickness parameter.

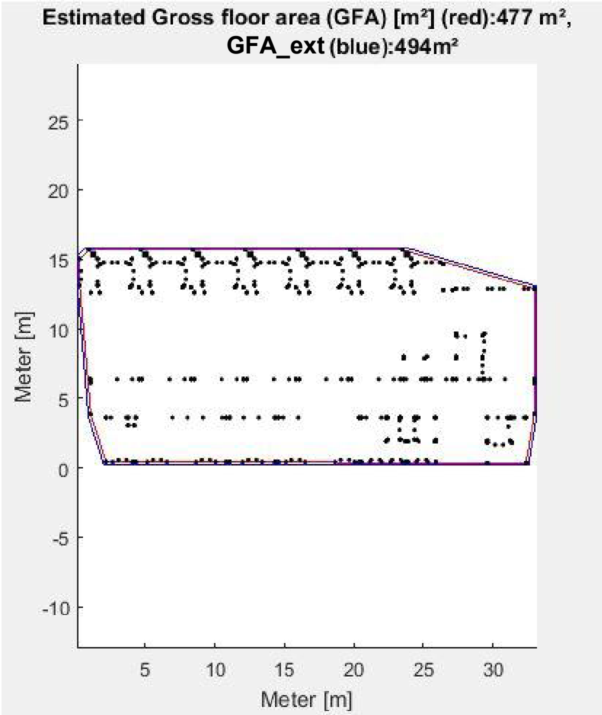

Figure 5-35: Estimated gross floor area for the hospital dataset (case study 2)

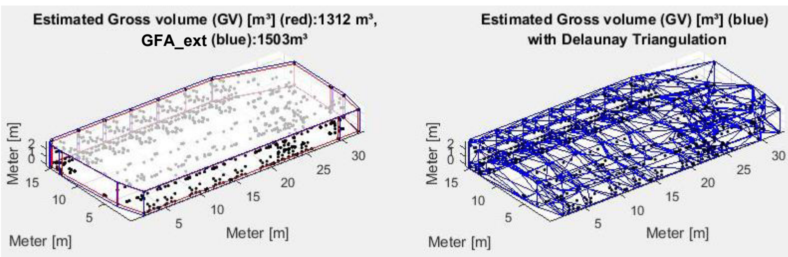

Figure 5-36: Estimated gross volume for the hospital dataset (case study 2)

The mortar, plaster and screed, gypsum and tiles model results are also too high which can be attributed to a to high thickness parameter of the wall, floor and ceiling coverings, which needs further testing in practice. The remaining, measured material masses fit into the model intervals, except for glass where the model values are higher.

Table 5-17: Aggregated material inventory of hospital story (case study 2) in [kg] for the baseline scenario

Material	Model results			Deconstruction value[18]
	(min) mass [kg]	(exp) mass [kg]	(max) mass [kg]	mass [kg]
Concrete (without rebar)	69769	199815	299847	47781
Masonry, Brick	173102	188281	298756	41671
Mortar/Plaster/Screed	21729	50309	101089	16058
Gypsum, Gypsum Cardboard	6105	7711	15422	702
Tiles, Sanitary ceramics	6416	6453	35395	854
Steel	743	6196	28763	2514
Copper, Brass (excl. cables)	0	0	0	170
Aluminum	0	0	0	0
Glass	589	1206	2335	362
Timber (treated)	581	2847	5808	1345
Plastics (PP,PE)	46	46	46	195
Plastics (PVC) (excl. cables)	1173	1173	2879	1393
Insulation	99	243	482	404
Cable	211	336	456	353

And, the material inventory is further aggregated to the assigned recycling and disposal paths (see Table 5-19). Table 5-19 shows the minimum, expected and maximum deconstruction masses that are designated to one of the listed categories of material recycling (secondary raw material use), energetic recycling (combustion), backfilling (e.g. onsite or in mining) and disposal on disposal sites. The minimum and maximum

[18] Values verified from industrial partners during the selective dismantling and deconstruction of the case study 2 building. These values are partly measured by weighting of the building elements (interior fittings and technical equipment, floor and ceiling covering) or calculated based on experience values (main building structure).

values are calculated according to section 4.3, where mainly the building element thickness is varied in the range of standard construction values. The material density is not varied. The expected values are based on sensor information, which can themselves be subject to uncertainty, which cannot be quantified here. Based on the aggregated material inventory, the recycling and disposal cost are calculated (see section 5.2.3). For the scenario construction, the building element properties are varied according to the scenario construction described in section 4.3. The baseline scenario (no. 14) includes: reinforced concrete ceilings, reinforced concrete floors, brick masonry walls, timber-framed windows and timber-framed timber doors. The electrical equipment is assumed to consist mainly of PVC except for the copper share in the wiring and the large aluminum distribution box for the whole story. For the best and worst material scenarios, the materials from ceilings, floor, walls, windows and doors are varied, e.g. the walls in the best case (regarding the deconstruction time) are made of unreinforced concrete and in the worst case of timber (see Table 5-18). The materials of the electrical equipment (DIN276 no. 44411-44441) are not changed, but extended by the TEQ water and waste water (DIN276 no. 41000-41999) and TEQ heating (DIN276 no. 42000-42999). Here, on average 3.44 potential material variations per building element are considered (with TEQ elements). Without TEQ elements this value is considerably higher with 5.22 materials per building element. A detailed building element inventory based on its raw materials is omitted here as it consists for case study 2 in a list with more than 1100 rows, including the walls, floor, ceiling, windows, doors, technical equipment of electrical power supply (TEQ Power), drinking water and waste water (TEQ TW, TEQ AW). Based on the recognized building elements, DIN numbers are assigned to the building elements and surface, volume and mass are assigned or calculated. Assigned values are the zero surfaces of TEQ Power elements and the standard value of 0.2 kg per electrical outlet. Also, the material information of the building elements is given and the reference room where the building element is located is reasoned.

Table 5-18: Material variation in the scenario construction of case study 2

DIN 276	Building element	Best material	Expected material	Worst material
324	Floor	6: Artificial resinate stone	1: Reinforced concrete	1: Reinforced concrete
325	Floor covering	7: Concrete stone	20: PVC	11: Tiles
331	Exterior walls	2: Unreinforced Concrete	3: Masonry Brick	16: Timber
341	Interior walls	2: Unreinforced Concrete	3: Masonry Brick	16: Timber
345	Wall covering	8: Plaster	11: Tiles	9: Gypsum/ Plasterboard
351	Ceilings	16: Timber	1: Reinforced concrete	1: Reinforced concrete
353	Ceiling covering	8: Plaster	9: Gypsum/ Plasterboard	9: Gypsum/ Plasterboard
3341	Doors	12: Steel	16: Timber	15: Glass
3342	Windows	12: Steel	16: Timber	16: Timber
41112	TEQ WWATER Pipe	12: Steel	12: Steel	1: Reinforced concrete
41243	TEQ DWATER Pipe	12: Steel	12: Steel	13: Copper
41262	TEQ WWATER Basin	12: Steel	11: Tiles/Ceramic	11: Tiles/Ceramic
41265	TEQ WWATER WC	12: Steel	11: Tiles/Ceramic	11: Tiles/Ceramic
41266	TEQ WWATER Shower	12: Steel	11: Tiles/Ceramic	11: Tiles/Ceramic
41267	TEQ WWATER Bathtub	12: Steel	11: Tiles/Ceramic	11: Tiles/Ceramic
42310	TEQ HEAT Radiator	12: Steel	12: Steel	12: Steel
44411	TEQ POWER Wiring	22 - Cable	22 - Cable	22 - Cable
44421	TEQ POWER Small Distribution Box	20 - PVC	20 - PVC	20- PVC
44422	TEQ POWER Large Distribution Box	14: Aluminum	14: Aluminum	14: Aluminum
44441	TEQ POWER Outlets (Switch, Socket)	20 - PVC	20 - PVC	20 - PVC
45111	TEQ IT Emergency outlet	20 - PVC	20 - PVC	20 - PVC

Table 5-17 includes the material inventory that aggregates the detailed building element inventory according to the inherent materials into 29 material categories. The here displayed material categories are reduced to the actually used ones. In this example, the aggregated inventory is reduced to the inherent material categories. The material inventory can be further aggregated to the assigned recycling and disposal path (see Table 5-19). Table 5-19 shows the minimum, expected and maximum deconstruction masses that are designated to one of the listed categories of material recycling (secondary raw material use), energetic recycling (combustion), backfilling (e.g. onsite or in mining) and disposal on disposal sites.

Table 5-19: Recycling paths with estimated material masses [t] for case study 2 for the baseline scenario

Recycling paths	Minimum mass		Expected mass		Maximum mass	
	[t]	[%]	[t]	[%]	[t]	[%]
Material recycling	2	0.7	8	1.7	32	4.0
Energetic recycling	2	0.7	4	0.9	9	1.1
Backfilling	271	96.4	445	95.7	735	92.8
Disposal [t]	6	2.1	8	1.7	16	2.0
Total [t]	**281**	**99.9**	**465**	**100.0**	**792**	**99.9**

5.2.3 Part B: Deconstruction project scheduling and optimization

In this model part, deconstruction activities and their durations are derived from the previously calculated building elements and are grouped to activity sets for each scenario. The activity duration derivation and the grouping are described in section 4.4.1 in detail.

In case study 2, building elements are grouped by their building element types and trades, e.g. interior and exterior walls into ‘walls’, or electrical outlets, lamps and switches into ‘TEQ Power’ of all electrical equipment in a room. Windows and electrical equipment are room-wise grouped into deconstruction activities, while the building elements doors, ceilings, walls and floors/foundations are grouped level-wise. As here is only a single level, they are aggregated into a single activity per building element type. In this case study, 62 activities are derived that include the dummy project start and end activities. The remaining 60 activities are the deconstruction of floor, floor coverings, walls, ceilings, ceiling coverings, doors, windows per room and the technical equipment for power (and emergency) supply, water supply and heat supply per room. Table 7-6 (Appendix V) shows the list of scheduled activity sets in case study 2, with their durations [h] per activities in the 9 considered deconstruction modes. This project work breakdown structure describes the hierarchical order of building elements and their related project activities (Table 7-6, Appendix V). If activity duration is zero, it does not automatically mean zero duration but it rather indicates that the activity-mode combination is not allowed.

Like in case study 1, the scheduling of the 62 activity sets follow a zero-lag finish-start predefined precedence due to technical constraints, organizational or logistic issues that follows the general deconstruction precedence presented in Figure 2-8.

In case study 2, 62 activities (network nodes) and 166 precedence relations (edges) describe the scheduling problem. The project network graph (see Figure 5-37) shows the logical precedence of the required deconstruction activities. Figure 5-37 shows all precedence relations in case study 2 in the top graphic, while in the bottom graphic the main part of the graphic with the sequential activities is shown. After project start, all doors, windows and technical equipment (TEQ AW, TW, POWER) are removed from the building in the potentially parallel deconstruction activities. Then, the wall covering (activities 25, 40) and the ceiling covering (activities 41, 55, 6, 26) is deconstructed in some rooms where a covering was detected. Subsequently, the floor covering is conjointly removed in all rooms (activity 3). After the deconstruction of these buildings' interior fittings, the whole structure is demolished including ceilings, walls and the foundation or floor slab. The recommended precedence of deconstruction activities is the decontamination of the building, followed by gutting and finally the demolition of the structure (except for the basement). For the case study 2, the considered building elements include for simplicity reasons only a part of the complex hospital building structure, which can be seen in Figure 5-28.

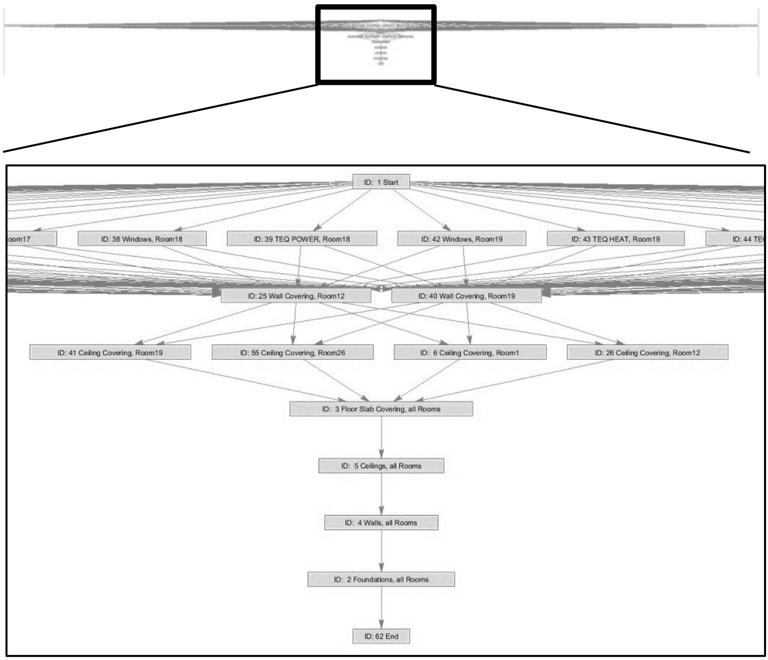

Figure 5-37: Project network graph of case study 2 - Hospital St. Georg, Bad Pyrmont

In this case study, nine modes for deconstruction activities with in total 51 different renewable resources consisting in machines, staff and locations (#:30 rooms) were used. The timely granularity of the model was selected to be 75 minutes. For this problem size, the computational effort accounts for about 70 minutes. For larger problem sizes (e.g. the whole hospital building), the time granularity has to be further reduced to ensure model solvability and to manage computational effort. This would come along with a decreased differentiation of the activity durations and thus a more inaccurate schedule and resource assignment.
Similarly like in case study 1, it can be stated that per deconstruction activity on average 4.5 potential modes are possibly applicable on the inherent building elements and on average 3.78 different resources (without locations) are necessary to perform a mode. Furthermore, a

resource factor of RF = 0.083 and an average resource strength RS = 0.0014 over all resources and modes demonstrate the resource scarcity in this case study problem. As both values are very low in the interval of [0;1], this indicates a scheduling problem that is rather difficult to solve. The restrictiveness RT depicts the degree of parallel activities in an acyclic project network. In this case study, the restrictiveness value is RT = 0.967, reflecting the high parallelism and the rather difficult scheduling problem of deconstruction activities in case study 2.

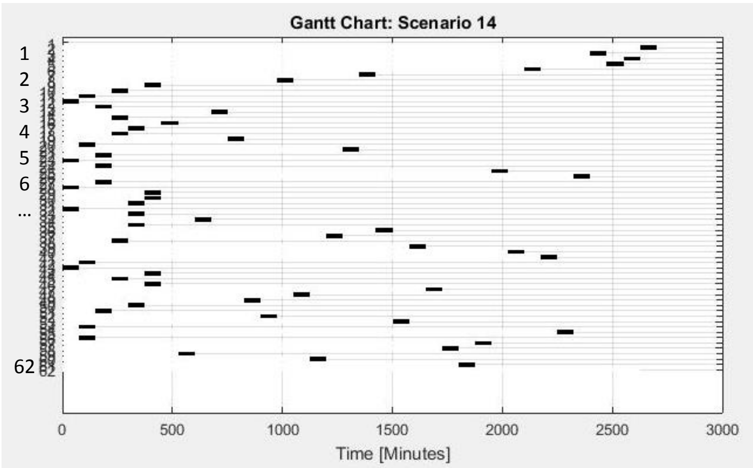

Figure 5-38: Gantt chart without precedence relations for all activities (y-axis) of baseline scenario 14 for case study 2 over project time t (x-axis)

The resulting schedules represented by Gantt charts of the baseline scenario can be seen in Figure 5-38, Figure 5-39 and Figure 5-40 and are shown per scenario in Figure 5-41. Figure 5-41 shows the optimal schedules in all 27 scenarios with differing mode selections of the deconstruction activities. The named modes and their resource demand are detailed in Table 5-4 (case study 1).

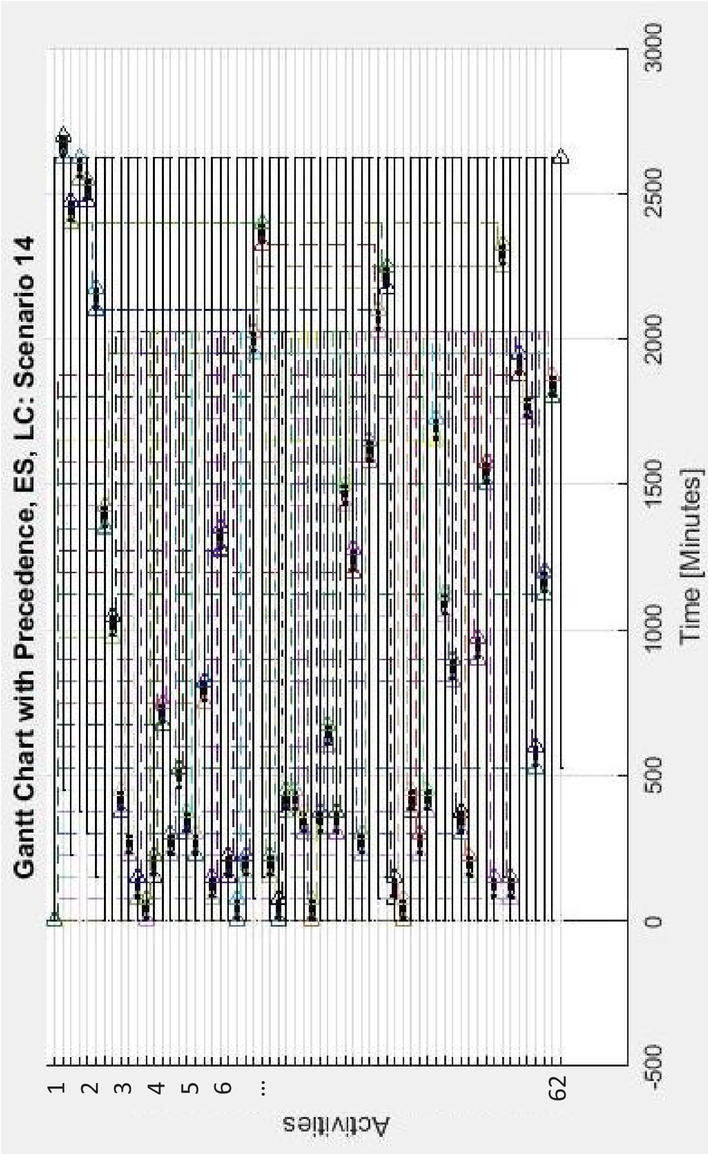

Figure 5-39: Gantt chart with precedence relations for all activities (y-axis) of baseline scenario 14 for case study 2 over project time t (x-axis)

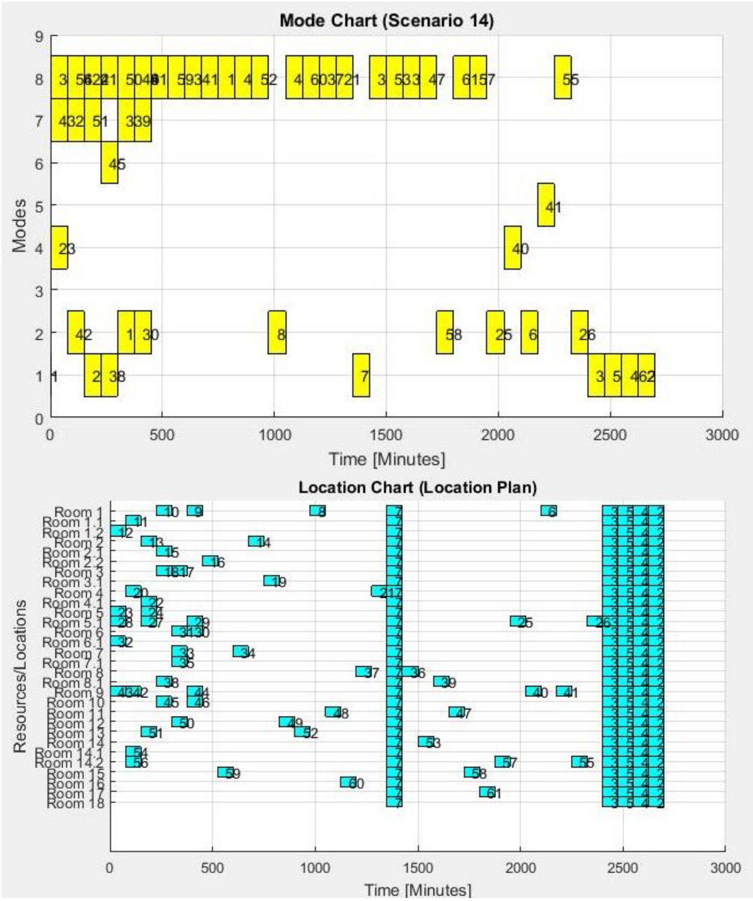

Figure 5-40: Mode Gantt chart (top diagram) and location chart (bottom diagram) with all modes (y-axis) and respectively all rooms (y-axis) over project time t (x-axis) for the baseline scenario 14 in case study 2

Figure 5-38 shows the Gantt chart of baseline scenario 14 without precedence relations and Figure 5-39 shows the precedence relations that are represented by dashed arrows and earliest start and latest completion time frames (horizontal lines with vertical markers). Figure 5-40 shows the mode assignments of all activities (top) and the utilization of the scarce renewable resource ‘location’ (bottom), where in both diagrams the numbers on the activities represent the activity IDs.

In the model, the resource profile of the optimum schedule in the baseline scenario can be displayed where the optimum resources are a hydraulic excavator with four different extensions, hand-held hammer and machine operator and normal staff (similar to Figure 5-13). Also, all 30 rooms are modeled as locations and their capacity profile can be calculated and displayed over project makespan (similar to Figure 5-14). This figure shows both types of deconstruction activities that are either planned per room (e.g. deconstruction of windows) or planned over all locations (e.g. deconstruction of ceilings).
The project costs are calculated for case study 2 as described in section 4.4.6 based on the one hand on the resulting cost from the optimal schedule per scenario and on the other hand on the recycling revenues and disposal costs per scenario. Like in case study 1, main sources of the cost calculation are (BGL 2015; BRTV 1995, 2014; Girmscheid and Motzko 2013 p. 182). Based on monthly cost rates for depreciation, interest rate and repair of equipment (BGL 2015), the size of the carrier machine and the assumption of 170 service hours per month (Girmscheid and Motzko 2013 p. 215), the hourly equipment cost are calculated[19]. Here, repair cost are usually calculated by a 10% rate on the labor cost for operating the equipment as the operator is performing maintenance and repair outside of the operating time (Girmscheid and Motzko 2013 p. 218). In the model, a MS Excel sheet with standard cost rates is provided that can be easily adapted to different regional costs and the values are automatically imported into the model. And, this can be easily adapted and extended by the user to his/her current equipment and machinery.

[19] See (Girmscheid and Motzko 2013 p. 213f.) for further information on the structure and the calculation of equipment cost. However, fuel costs are not considered here, but can be assumed with 100-175 g (0,12 -0,21 l fuel per working hour) and a related lubricant consumption cost of 10 % – 12 % of fuel costs (Girmscheid and Motzko 2013 p. 218).

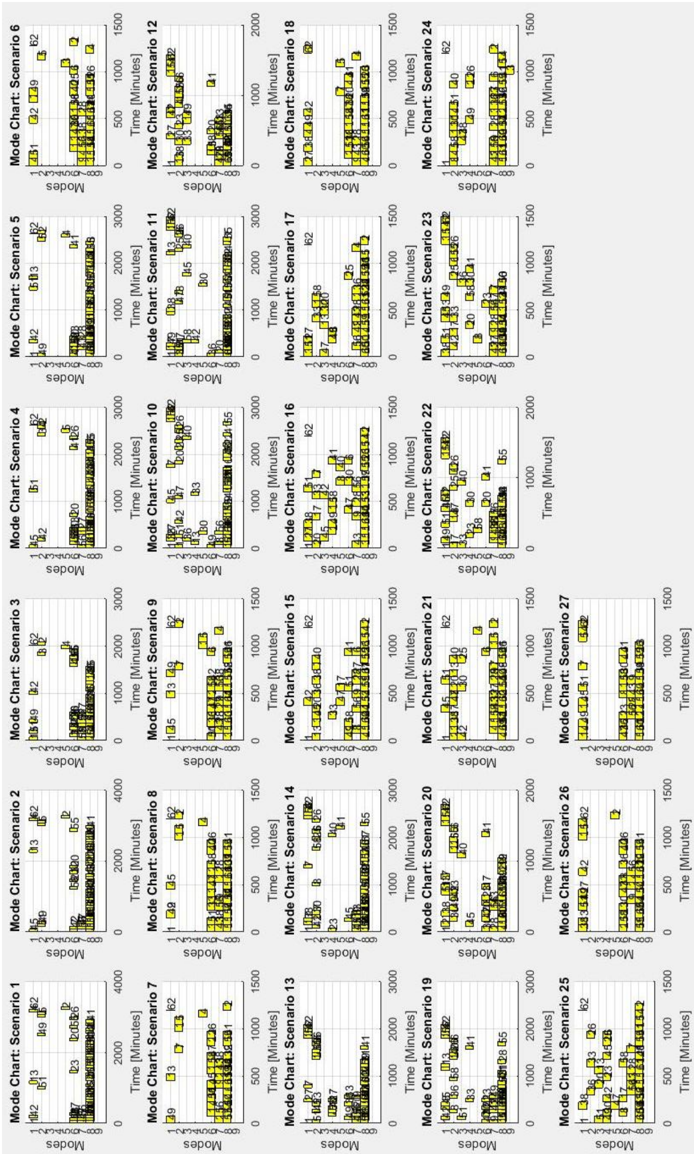

Figure 5-41: Gantt charts with optimal modes (y-axis) of all case study 1 activities in each scenario respecting precedence constraints over project time t (x-axis)

Labor costs are calculated according to the current tariff of the German deconstruction association (Deutschen Abbruchverbands) and the German construction industrial union (Industriegewerkschaft Bau) and the according to the „Bundesentgelt- und Rahmentarifvertrag für Beschäftigte des Abbruchgewerbes“ and the hourly rate of standard wages (Lohngruppe 3+4) (BRTV 1995, 2014; Girmscheid and Motzko 2013 p. 182). Thus, hydraulic excavator operator staff (95 €/h) and normal staff (34 €/h) rates are distinguished[20] and calculated into project cost by their deployed hours for the respective project. Here, the medium wages are assumed based on standard productivity. If the scheduled staff is less productive, the project calculator and decision makers need to adapt this value accordingly. And, for each deconstruction activity, the necessary number of staff both for the operation of equipment and additional auxiliary staff (banksman) is considered (Girmscheid and Motzko 2013 p. 218).

Like in case study 1, to calculate the recycling and disposal costs of the project, the designated recycling and disposal of fractions follow the hierarchical recycling paths of KrWG. In the model, the assignment of the building element masses to recycling and disposal fractions follow the state-of-the-art technology and are dependent on the respective material. Here, fractions of metal (steel, copper, aluminum, electric wires) and glass are assumed to be recycled and to gain recycling revenues. Material fractions of timber, textiles, and plastics (PE, PVC) are assumed to be energetically used and combusted. Mineral fractions of concrete, screed, mortar, plaster, tiles, bricks and artificial stones are assumed to be backfilled onsite, in road construction or in mining. Materials and building elements made of gypsum, insulation materials, asbestos and other hazardous materials are assumed to be deposited in landfills. Energetic use, backfilling and disposal are calculated at the current cost per ton [EUR/t].

[20] Labour cost were given by experts in December 2014 (project meeting, Hameln).

The recycling and disposal rates are calculated based on the mentioned recycling and disposal assignment of the material fractions for case study 2 and are listed in Table 5-19. The percentage of the fractions of material recycling, energetic recycling, backfilling and disposal are calculated in relation to the total deconstruction mass. In case study 2, the recycling rate is 4 % (separated in 3 % secondary raw material recycling and 1 % energetic recycling) and the disposal rate is 96% (94 % backfilling and 2 % disposal). As the recycling and disposal fractions are only assumed, and the local and regional recycling options on near construction sites often are not known due to a structural information deficit. Thus, the identified recycling and disposal rates might not necessarily reflect the real values.

Table 5-20: Project cost [EUR] for baseline scenario in case study 2

Project costs	**Minimum cost [EUR]**	**Expected cost [EUR]**	**Maximum cost [EUR]**
Costs for deconstruction activities	101760	137800	183880
Costs for sorting activities	0	0	0
Cost for disposal	5605	9098	16721
Revenues for raw materials/ recycling	-188	-1065	-5014
Total project costs	**107180**	**145830**	**195590**

The expected disposal costs and recycling revenues in the model are based on actual prices of respective waste fractions as well as raw material and recycling material prices for Niedersachsen (Containerdienst-regional.de 2016; Schrott.de 2016). These prices may vary depending on international raw material prices or between regions and can only be seen as a sample calculation. Transportation, sorting, or crushing costs are not included yet in the calculated variable deconstruction costs[21] and also container rent is not included yet. Table 5-20 shows the

[21] The interested reader is referred to (Schultmann 1998 pp. 85–101) for details on the calculation and inclusion of these cost.

calculated disposal costs and recycling revenues in case study 2 according to formulas (4.52) and (4.53) (related to building elements).

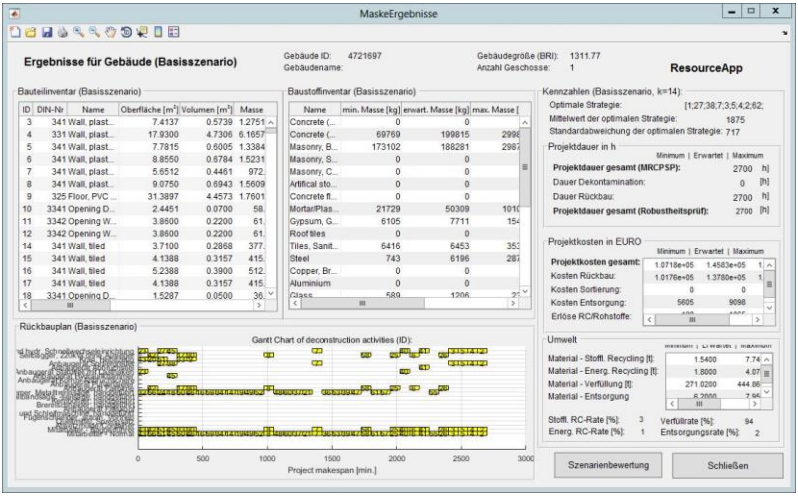

Figure 5-42: Graphical user interface with model results for the hospital dataset (case study 2), based on 75 minutes time slices

Also, the model calculates recovery costs of materials per kilogram or ton. This value is calculated as the amount of the respective material divided by the total project cost. This value is calculated as described in case study 1 (section 5.1.3). Figure 5-42 shows the model results for the baseline scenario of case study 2 with its building element inventory (left), material inventory (center), Gantt chart of the scheduled deconstruction activities (bottom), calculated project duration (right top), calculated project cost (right center) and calculated material recycling, energetic recycling, backfilling and disposal rates (right bottom). The building element inventory in the left table in Figure 5-42 includes the listed information as described in section 4.3.2. The recovery cost can be found in the center table of Figure 5-42 by scrolling to the right.

Figure 5-43 and Figure 5-44 show the optimum project makespan in all scenarios and their resulting project cost. In Figure 5-43, the sorted optimal project makespan distribution over all scenarios is shown. This can be seen as the density function of the optimal project makespan over all scenarios, if the 27 scenarios are assumed to be equally distributed. The numbers in the diagram label the respective scenarios.

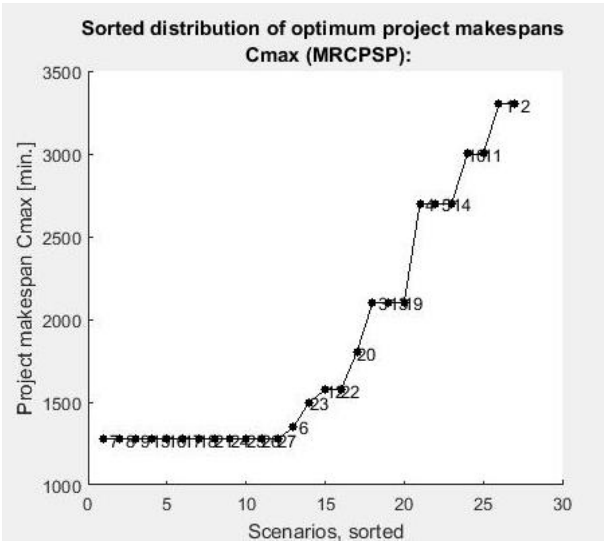

Figure 5-43: Distribution of optimal project makespan C_{max} (MRCPSP) cost over all 27 scenarios for a scenario comparison

Figure 5-44 shows the distribution of project cost (according to formula (4.54) related to applied resources) and project makespan for all scenarios. Here, often a linear relation is assumed in literature which cannot necessarily be stated for the deconstruction project in case study 2. Furthermore, it is noticeable that in the left corner of Figure 5-44, there are three scenarios {21, 24, 27} with negative total cost. This equals to higher recycling revenues than the deconstruction activity costs due to a high assumed metal fraction in these scenarios. The numbers in this diagram label the respective scenarios, where the optimal project makespan and the resulting project cost were calculated. This might provide the decision maker with first insights on the expected project durations and cost under different scenarios (site conditions).

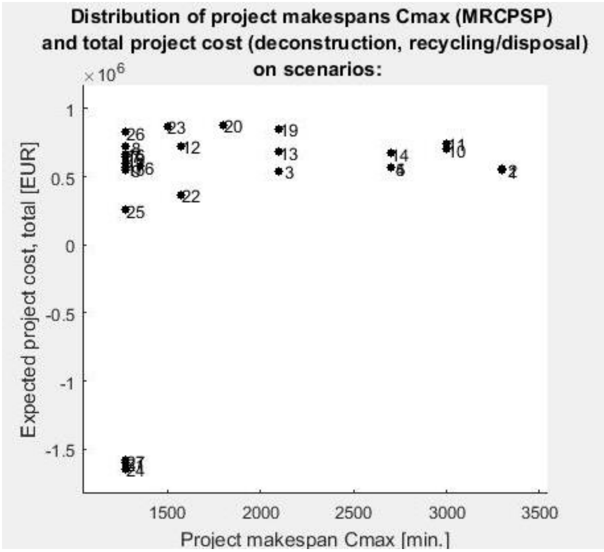

Figure 5-44: Distribution of optimal project makespan C_{max} (MRCPSP) and resulting project cost over all 27 scenarios for a scenario comparison

However as discussed already in sections 4.4.4 and 4.7.2, the computational effort to calculate the optimum resource assignment and the minimum project makespan for all scenarios is quite high and strongly depends on the chosen model granularity (activity grouping and time slices). Here, time slices of 75 minutes where chosen that result in the following problem construction time [sec], problem solution times [sec] and CPLEX iterations. In total, the computational effort regarding the solution of the MRCPSP for all 27 scenarios is summing up to about 54 minutes[23]. Table 5-21 shows the detailed computations effort per scenario. On average, 61 seconds are required for the problem construction and on average 59 seconds and 1.13 million iterations are necessary to find the optimal solution by CPLEX[22]. However, as can be seen in Table 5-21, the 2nd and 10th scenario are taking exceptionally longer for their problem construction and problem solution.

Table 5-21: Computational effort of problem construction and problem solution of case study 2 [sec][23]

Scenario No.	Problem construct. [sec]	Problem solution [sec]	Number of iterations	Scenario No.	Problem construct. [sec]	Problem solution [sec]	Number of iterations
1	58.20	71.15	725898	**15**	55.13	13.21	91021
2	56.85	506.188	11512955	**16**	82.06	18.54	172490
3	31.35	27.01	804664	**17**	68.53	16.23	125720
4	35.21	65.82	1451197	**18**	149.64	14.70	63748
5	48.73	45.43	885401	**19**	32.12	16.07	299024
6	64.18	9.18	128950	**20**	34.14	5.82	195416
7	65.07	7.67	98418	**21**	39.65	11.82	49949
8	68.09	7.15	184802	**22**	36.32	9.98	141742
9	118.61	8.70	149164	**23**	58.10	16.48	178810
10	39.56	575.25	11363554	**24**	68.24	12.78	91043
11	45.27	46.82	783507	**25**	70.06	13.50	94299
12	61.45	7.89	80899	**26**	78.10	9.40	299534
13	38.09	21.79	456672	**27**	99.68	15.04	87097
14	51.43	21.48	149673				

5.2.4 Part C: Identification and selection of robust deconstruction strategies

In this model part, a robust deconstruction strategy for case study 2 is identified according to the decision makers' risk preference. In case

[22] Furthermore, the following default CPLEX options are used: maximum number of iterations (MaxIter): 9.2234e+18, branching strategy (BranchStrategy): 'maxinfeas', maximum solution time (MaxTime): 1.0000e+75 seconds, node searching strategy (NodeSearchStrategy): 'bn'.

[23] Due to the high computational memory demand of this case study, the model results were calculated on a different server than case study 1 with 64bit operating system and equipped with Intel® Core ™ i7-4930K CPU (3.40 GHz) and 64 GB working memory.

study 2, 27 optimal deconstruction strategies are identified by the model. For this purpose, the identified optimum deconstruction strategies of each scenario in model part B (Figure 5-43) are used to plan each scenario with each optimal deconstruction strategy. The resulting project makespan C_{max} of all deconstruction strategies and all scenarios is shown in Figure 5-45. Figure 5-45 shows that except for single scenarios 9, 15, 16 ,18 and 27, the deconstruction strategies lead to similar results over all scenarios. In the mentioned scenarios, however, the differences with respect to the total project makespan are visible.

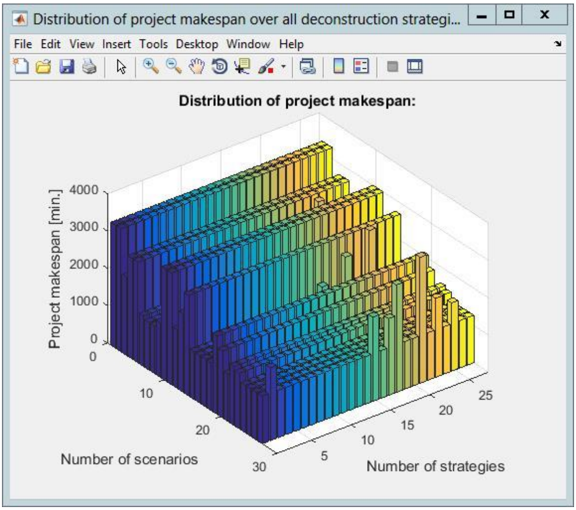

Figure 5-45: Distribution of project makespan over all deconstruction strategies and scenarios after stress test (model output)

Figure 5-46 shows the distribution of the project deconstruction cost (left) and the distribution of the project makespan (right) over all deconstruction strategies and scenarios after the stress test. With respect to project cost in the left diagram, it becomes obvious, that despite similar project makespans of deconstruction strategies in a single scenario, the resulting project cost differ significantly.

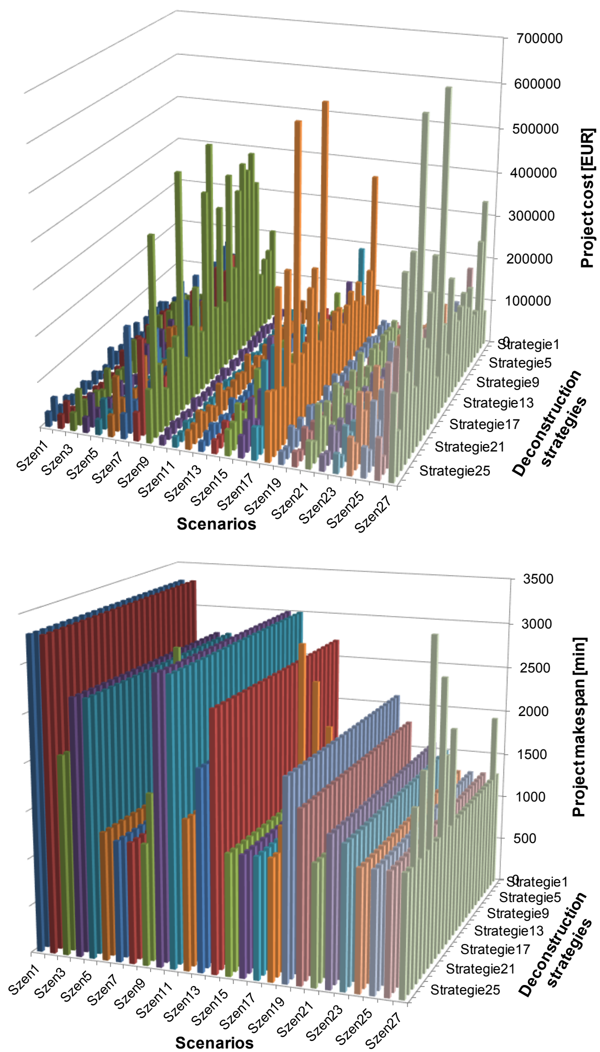

Figure 5-46: Distribution of deconstruction cost (top) and project makespan (bottom: see also Figure 5-45) over all deconstruction strategies and scenarios after stress test

Figure 5-47 shows the frequency of the deconstruction strategies resulting project makespans over all scenarios in a histogram. Here, in about half of the scenarios the deconstruction strategies result in a quite low project makespan with less than 1500 minutes (first histogram class). In the second half of the scenarios, the deconstruction strategies result in higher project makespans, with up to almost 50% higher project makespan. And, Figure 5-47 shows that the strategies' performance with respect to the project makespan differs less than in case study 1.

As described before in section 4.5, the deconstruction industry is rather characterized by risk-neutral to risk-averse decision makers. Risk-averse decision makers define the most robust project schedule either by absolute mini-max (regret) criterion or by the best-performing deconstruction strategy in the worst case scenario. Risk-neutral decision makers prefer a most robust schedule with either a minimum average absolute regret criterion or a minimum Laplace criterion.

In case study 2, the most robust strategy or strategies are defined by the minimum average absolute regret criterion. In this research contribution, the total optimality-robust deconstruction strategy $\Pi^*(z_k)$ is of specific interest, which can be identified by the minimum average deviation from the minimum project duration in all scenarios (absolute regret) (see also section 3.2.4). When the minimum average deviation (absolute regret) for a deconstruction strategy Π $AR(\Pi(z_k)) = 0$ for all scenarios $z_k \in Z$, this solution comprises a total optimality-robust solution.

The generated deconstruction strategies can be found in Table 7-7 in Appendix VI for case study 2 with their calculated robustness measures of average (or expected) project makespan (C_{max} μ) (under the assumption of equally distributed scenarios), their variance project makespan (C_{max}, σ^2), their standard deviation project makespan (C_{max}, σ), their μ-σ-rule project makespan and their average absolute regret. The deconstruction strategies (here: # = 27) itself represent the number of activi-

ties that are planned in the respective modes (here: # = 9) that are delimited from each other by the rectangular brackets.
It can be seen in Table 7-7 (Appendix VI), that there are several deconstruction strategies with a zero average absolute regret, which can all be advised to the decision maker as totally and equally robust deconstruction strategies under the assumed 27 scenarios. In case study 2, these robust deconstruction strategies are $\Pi = \{3,4,12,14,19,20,22,24,27\}$. Other strategies like strategies 9, and 10 only have a small absolute regret, but therefore would not be recommended to the decision maker at this stage. The best deconstruction strategy in the worst-case scenario is strategy 1 with an average $C_{max} = 1863$ and an absolute gret $AR(\Pi(z_k)) = 193$. As the absolute regret of the optimum strategy of worst case scenario is not zero, the explicit hedging against the worst case it is not recommended to the risk-averse decision maker.

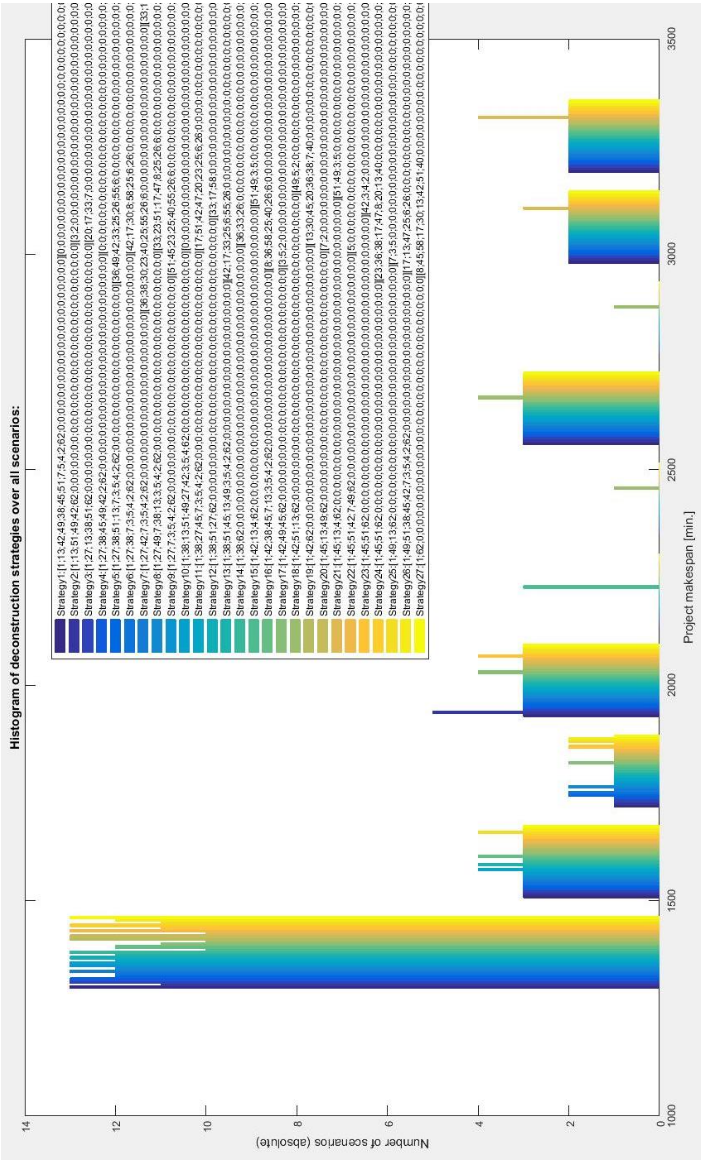

Figure 5-47: Histogram of all deconstruction strategies and their average project makespan

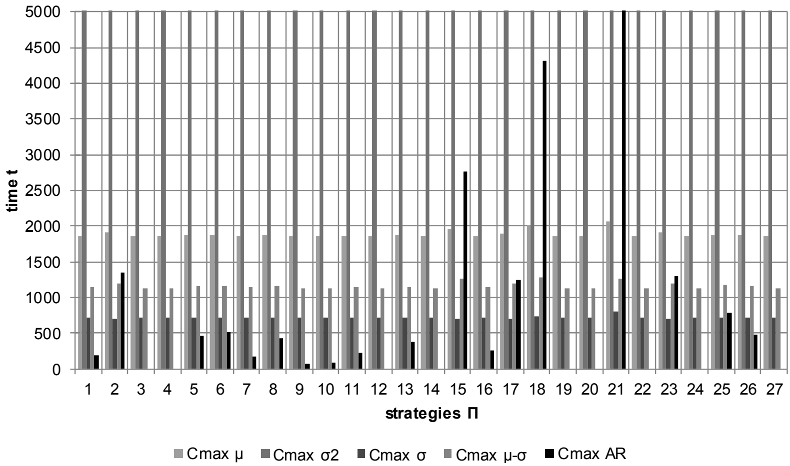

Figure 5-48: Visualization of the identified deconstruction strategies and their robustness measures (average absolute regret: black) of case study 2 after the stress test on all scenarios, in ascending order of the strategy IDs

The data in Table 7-7 (Appendix VI) is visualized in Figure 5-48 and Figure 5-49 with a predefined maximum limit of the y-axis for a better clarity of the model results. Figure 5-48 shows the unsorted deconstruction strategies and their robustness criteria values after the stress test of the strategies on all scenarios. Figure 5-49 shows the sorted deconstruction strategies according to their absolute regret value sorted in ascending order. In both figures, the ten totally robust strategies with average absolute regret (black) AR=0 can be seen in Figure 5-49. Also, the strategy $\Pi = \{9{,}10\}$ with comparably low average absolute regret values below 200 [time units] are visible, that also might become interesting deconstruction strategies in the case of information updates and a local search for robust and feasible deconstruction strategies under new information and conditions.

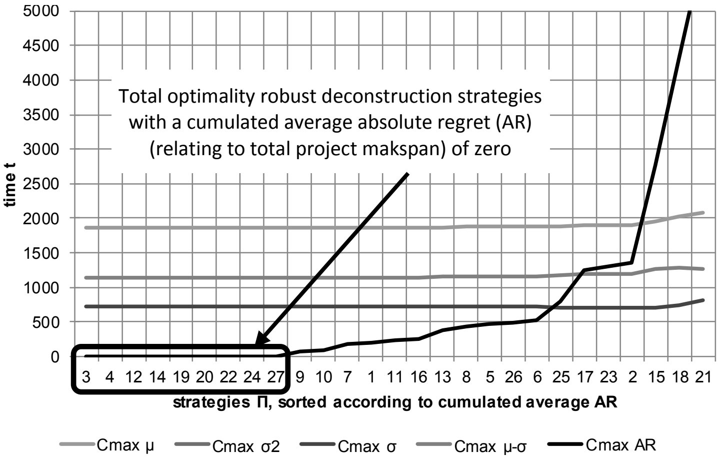

Figure 5-49: Visualization of the identified deconstruction strategies and their robustness measures of case study 2, in ascending order according to the deconstruction strategies' average absolute regret values (black) and the related mean μ and standard deviation σ robustness criteria values

Figure 5-50 shows the sorted average project makespan of all deconstruction strategies. In case study 2, it becomes obvious about half of the possible deconstruction strategies obtain a relatively low average project makespan, while the project makespan of one remaining quarter of the deconstruction strategies have higher average project makespans and the other quarter have considerably higher project makespans. In Figure 5-51, the distribution of average project cost and average project makespan for all strategies over all scenarios are represented. Here, often a linear relation between project time and project cost is assumed in literature which is represented in this case by the linear trend line for the deconstruction project in case study 2. The numbers both in Figure 5-50 and Figure 5-51 label the respective numbers of the deconstruction strategies.

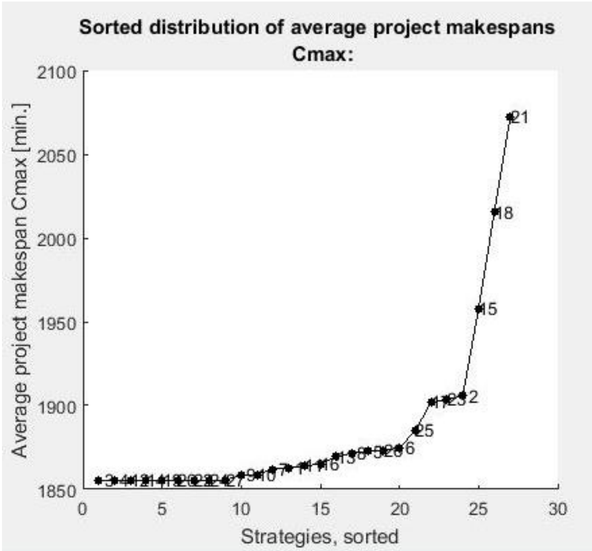

Figure 5-50: Distribution of average project makespan of all deconstruction strategies over all scenarios in case study 2

To compare the optimal solutions (deconstruction strategies) with zero average absolute regret with each other and to recommend the 'best' deconstruction strategy to the decision maker, several possibilities exist. Either average project makespan or average cost of the deconstruction strategies with zero absolute regret is compared. Or, both values are considered, e.g. in multi-criteria methods and a respective weighting of the two objectives is necessary. Here, first the deconstruction strategies with minimum average project makespan are selected (absolute robust strategies $\Pi = \{3,4,12,14,19,20,22,24,27\}$). If there is more than one deconstruction strategy with a zero absolute regret and the minimum average project makespan, then the deconstruction strategy with the minimum project costs is selected. Thus, the closest strategy to the point of origin is regarded as the 'best' solution. In case study 2, according to this procedure deconstruction strategy 4 is recommended to the decision maker.

In the baseline scenario 14 that can be seen as the deterministic case, deconstruction strategy 6 is chosen as the optimal strategy. Strategy 6 has an absolute regret of 512 time units and does not belong to the set of optimum strategies that could be recommended to the decision maker. Considering the robustness analysis and the resulting total project cost, strategy 4 proved to be a more robust strategy with a lower average total project cost over all scenarios.

Figure 5-51: Distribution of average project makespan and average project cost of all deconstruction strategies over all scenarios in case study 2

5.2.5 Verification and sensitivity analysis

To verify case study 2, there are several possibilities. This section verifies the model results via a plausibility check, if the calculated values are in a realistic material mass range and provides a sensitivity analysis to demonstrate the effects of varying risk preference parameters on model results.

The building inventorying part in model part A can be verified by literature values for the estimation method of building material masses. This building auditing method is based on the multiplication of material mass estimation factors by the percentage of materials that occur in the building (Gruhler and Böhm 2011 p. 50). In the case of an "Anstaltsgebäude" like the case study 2 hospital of the building type Ia, the following material mass estimation percentages are assumed (see Table 5-22).

In case study 2, a gross volume of 1503 m³ (see Figure 5-35) and a total mass of 280.51 t (min.), 458.82 t (exp.) and 762.65 t (max.) (Table 5-19) is calculated for the hospital level. The building part is constructed with masonry walls and reinforced concrete slabs, and thus falls into the building or construction type Ia. The estimation of material masses based on the percental estimation factors (in Table 5-22) are compared with the model-based building inventory values of case study 2 in Table 5-23 and are shown in Figure 5-52.

Table 5-22: Material mass estimations [%mass] for case study 2 based on gross volume estimation and on average percentages for different material categories[24]

Building / construction type	Material categories	(Gruhler and Böhm 2011 p. 50)
Building type I/II "Anstaltsgebäude" (solid construction, masonry and reinforced concrete)	Reinforced concrete Masonry Timber Metals Others	26 % 66 % 5 % 2 % 1 %

The isochromatic lines in Figure 5-52 represent same material categories, while the squares show the percentage-based estimation and the triangles show the model-based estimations. In Figure 5-52, it can be seen that some isochromatic lines lie closely to each other, while others are quite apart. In the case of concrete and brick masonry, the model calculated between 70 t and 300 t (concrete) and 194 t and 400 t (brick and

[24] According to (Gruhler and Böhm 2011 p. 50).

mortar/plaster/screed), while the percentage estimation has in a far smaller range between 73 t and 198 t (concrete) and a considerably larger range between 185 t and 503 t (brick). The expected concrete and masonry masses of the model of 200 t (concrete) and 239 t (brick and mortar/plaster/screed) lie very close to and in the verification ranges. The concrete calculation of the model is based on ceiling and floor slabs with a thickness of 0.2 m and in case study 2 both ceiling and floor slabs are included with the half thickness. For a profound validation, further tests of the model and case studies are needed. Furthermore, as discussed in case study 1 (section 5.1.6), in the current model, small deviations might result from the mass calculation of the walls due to the negligence of wall corners with adjoining rooms (see also section 4.3.2).

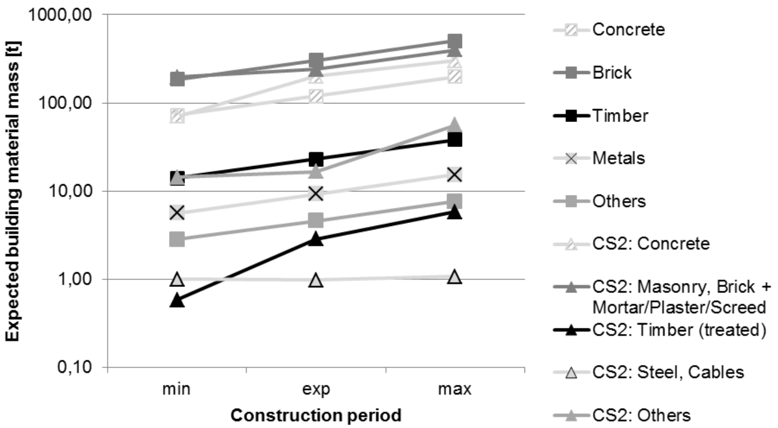

Figure 5-52: Comparison of building mass estimations [t] of percental estimation (squares) and model-based estimation for case study 2 (triangles represent minimum, expected and maximum values

In the case of timber, metals and other materials, the percentage estimation and the model result differ considerably. However, this might be the case because the percentage estimation values of (Gruhler and Böhm 2011 p. 50) are quite generic and are based on average values of recently constructed non-residential buildings of this class. On the one hand, the value relates to whole buildings instead of the here considered single story. On the other hand, the percentage-based estimation over all newly constructed buildings might not correctly represent the material masses of the particular case study 2 due to their very generic approach. However, it might serve as an indicator of the correct magnitude of the material mass fractions.

Furthermore, weighted detailed deconstruction material fractions and their masses of the second floor of the case study hospital can be found in Table 5-17. The calculated model results and the weighted values are discussed in section 5.2.1.

Table 5-23: Comparison of building mass estimations [t] of percental estimation (squares) and model-based estimation for case study 2 (data of Figure 5-52)

Total Material mass estimations [t]	**Percentage estimation based on (Gruhler and Böhm 2011 p. 50)**			**Model results for case study 2**		
	minimum [1]	**expected [2]**	**maximum [3]**	**minimum [1]**	**expected [2]**	**maximum [3]**
Reinforced concrete (26 %)	72.93	119.29	198.28	69.76	199.81	299.84
Masonry (66 %)	185.13	302.82	503.34	194.83	238.59	399.84
Timber (5 %)	14.03	22.94	38.13	0.58	2.84	5.80
Metals (2 %)	5.61	9.17	15.25	0.74	6.17	28.76
Others (1 %)	2.80	4.58	7.62	14.32	16.58	56.07
[1] based on 280.51 t; [2] based on 458.82 t; [3] based on 762.65 t						

Figure 5-53 shows that the relation between mass and volume in industrial buildings follow a declining line with increasing gross volume. In Figure 5-54, residential buildings can be seen with their relation between mass and volume. As hospitals are non-residential buildings but have similarities in the construction type and the room size, both Figure 5-53 and Figure 5-54 are used for a verification of model results.

In both diagrams of Figure 5-53 and Figure 5-54, the axes show the specific building mass [t/m³ GV] (y-axis) of industrial, single-family and multi-family residential buildings in relation to the buildings gross volume [m³] (x-axis) with a ±60% (left) and ±50% (right) deviation range (shaded area). Compared to the data displayed in Figure 5-53 and Figure 5-54, in case study 2 a range of the specific building mass ratio [t/m³] of 0.186 – 0.507 is calculated in the model. In both Figure 5-53 and Figure 5-54, it is shown how these values fit into these experience data. The expected value lies at 0.304 and is indicated with a black rhombus. It can be seen, that the specific mass value of case study 2 is rather low, compared to other industrial buildings (Figure 5-53) or other multi-story buildings (Figure 5-54, rhombuses). This might be because by the consideration of a single building story instead of a whole building with roof and foundations the specific mass might increase.

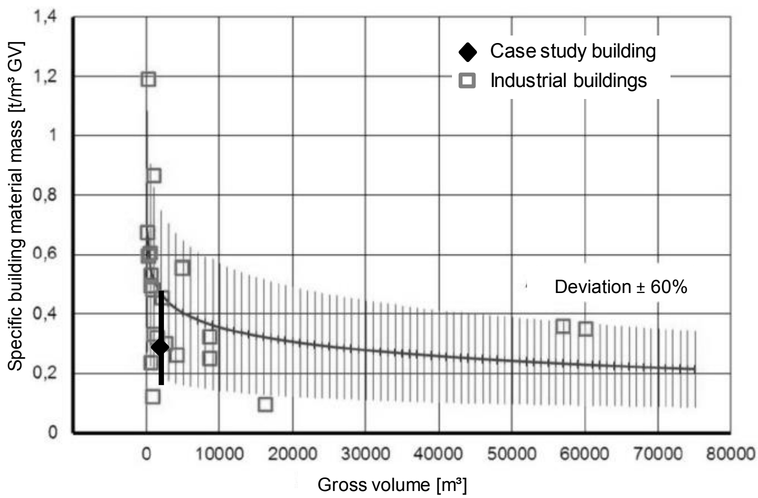

Figure 5-53: Relation between buildings' gross volume (x-axis) and its specific mass in t/m³ of gross volume (y-axis) for industrial buildings[25]

[25] According to (Müller 2013 p. 5f.), (accessed: 19.05.2016).

As discussed in case study 1 (section 5.1.6), a classical sensitivity analysis with a percental variation of model input parameters over a value range is not reasonable. Rather, different parameter constellations can be calculated by the model and the model results can be compared with each other. As this type of analysis is directly done in the proposed research contribution, the indirect sensitivity analysis is restricted here and also in case study 1 to an analysis of the influence of decision makers risk preferences (see also section 5.1.6).

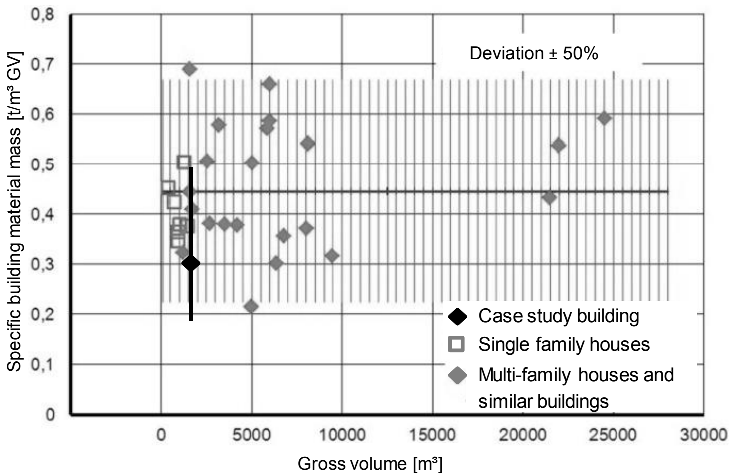

Figure 5-54: Relation between buildings' gross volume (x-axis) and its specific mass in t/m³ of gross volume (y-axis) for residential buildings (right, square: single family houses, rhombus: multi-family houses)[26]

[26] According to (Müller 2013 p. 5f.), (accessed: 19.05.2016).

In the proposed decision making case of deconstruction project planning, risk-averse decision makers are in the focus. However, their degree of risk aversion is not differentiated by the model yet. To analyze the degree of risk aversion the Hurwicz robustness criterion can be used, to show the effects of the risk preference graduations between risk neutrality and risk aversion on deconstruction strategy selection. The Hurwicz criterion maximizes or minimizes the linear combination of the minimum and maximum objective value of an alternative with an optimism parameter $\lambda \in [0; 1]$ (Scholl 2001 p. 136f.). If $\lambda = 0$, the decision maker is assumed to be very pessimistic (=mini-max criterion) and if $\lambda = 1$ the decision maker is very optimistic (=maxi-max criterion) (see also section 3.2.4).

Figure 5-55 depicts all 26 deconstruction strategies and the change of their objective value (project makespan) in relation to their degree of risk aversion. The lines in Figure 5-55 show, that there are some deconstruction strategies, that are stronger affected by the different risk preferences of decision makers, such as strategies $\Pi = \{18,10,21, \dots\}$ (from the top) which is reflected by a relatively steep gradient, while others like $\Pi = \{23,25, \dots\}$ (from bottom) are not or less influenced.

Similarly, the Hodges-Lehmann criterion applies a confidence parameter $q \in [0; 1]$ (Scholl 2001 p. 129) and combines the expectancy value μ over all scenarios with the pessimistic mini-max criterion, respectively the most unfavorable objective value. It is shown in Figure 5-26 that in this case deconstruction strategies $\Pi = \{18,10,21, \dots\}$ are very sensible to variances of the risk preferences, while others like $\Pi = \{19, 23,25,20,16, \dots\}$ are less or not sensible.

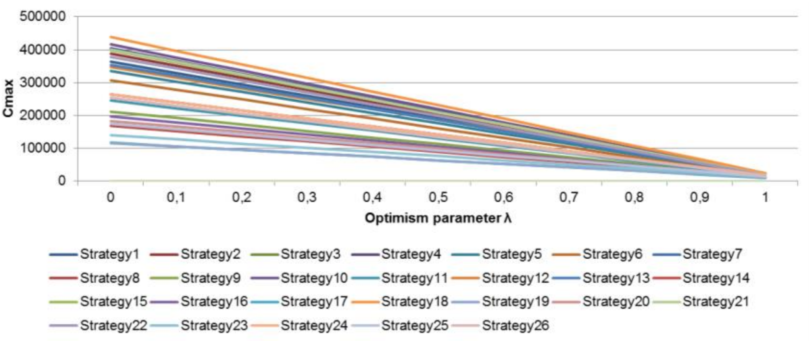

Figure 5-55: Robustness evaluation based on Hurwicz criterion with optimism parameter λ for case study 2

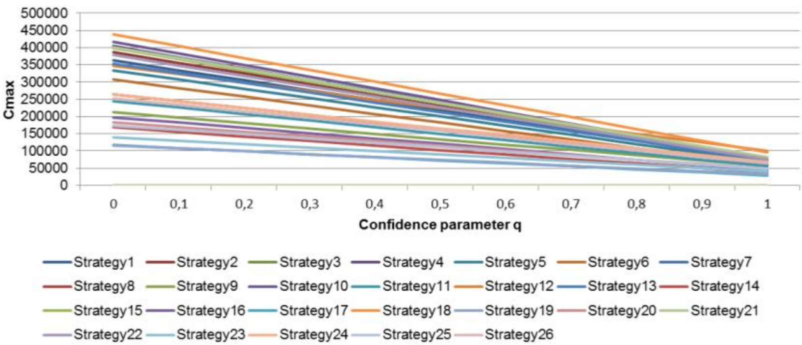

Figure 5-56: Robustness evaluation based on Hodges-Lehmann criterion with confidence parameter q for case study 2

5.3 Summary and discussion of the model application

5.3.1 Summary

The developed robust deconstruction project scheduling and decision support model (see chapter 4) was applied in two different cases to test its functionality and to verify the model results. The first, small case study focuses on the deconstruction project planning of a single-family residential apartment with four rooms and solely electrical equipment. The second, larger case study generates a robust deconstruction project planning of a hospital part with thirty rooms and electrical, waste and drinking water equipment as well as heating installations.

The developed robust deconstruction project scheduling and decision support model is implemented as a program in MATLAB 2015b (64bit) in an object oriented manner and is loosely following BIM structure regarding the hierarchical order of building, spaces and building elements. The model results are based on building data from an interface that can be automatically captured by sensors. Other necessary data for the inventorying of the building elements and the project planning parameters are either imported from MS Excel or entered by the user in three consecutive graphical user interfaces realized in MATLAB.

The application cases show that the developed approach and the realized model are working for different datasets and for different parameter constellations of the generated scenarios and also of user inputs (such as resource capacities). Case study 1 shows larger differences between the resulting average project makespan of the generated deconstruction strategies than case study 2. This might result from the repetitive and parallelized deconstruction schedule in case study 2 with thirty rooms and respectively a higher number of activities and a lower variation in average project makespan. In contrast, case study 1 consists of less potentially parallel activities which might have a larger impact on project makespan. Therefore, in the second case study, a different grouping of deconstruction activities (see also section 4.4.1) might lead to different results. For example, a higher degree of activity aggregation and consequently a lower number of activities will probably result in a higher impact of single activities on the model results with respect to the total project makespan and cost.

The developed model allows the decision maker to compare alternative deconstruction scenarios and alternative deconstruction strategies with respect to their total project makespan and their expected cost. This shows a range of possible project outcomes and this quantifies the risk inherent in the potentially varying building configuration and resource productivity. Compared with the deterministic case of both case studies, it can be stated that in both case studies the model recommends robust deconstruction strategies to the user that differ from the optimum deconstruction strategy in the deterministic case. The deterministic case is defined as the case when all project parameters are assumed to have their expected value (baseline scenario 14). In the other scenarios that are additionally considered to the deterministic case, other deconstruction strategies prove to be more quality robust over all scenarios in both case studies and thus are preferable for risk-averse decision makers. In the application cases, it could be demonstrated, that for example in case study 2 a cheaper deconstruction strategy can be chosen with the same robustness performance in all scenarios (see Figure 5-50).

Furthermore, the application cases and their verification indicate that the developed model provides reasonable and plausible material masses when compared to literature values (see verification sections 5.1.6 and 5.2.5). Also, in case study 1 the calculated project cost is in a realistic range (see sections 5.1.6). This allows decision makers to objectively inventory buildings and to quantify material masses and recycling and waste fractions.

Altogether, the proposed deconstruction project planning and decision support model can be seen as an improved decision making support for deconstruction project planner considering uncertainties in deconstruction project planning. This improves the current deconstruction project planning and decision making where only a single deterministic case (eventually combined with a thumbs-rule risk surcharge) is calculated and planned without considering potential operational uncertainties, which often results in project delays or cost increases.

5.3.2 Discussion

Although the application of the developed model showed several benefits in deconstruction project planning and improves decision support in deconstruction project planning under uncertainty, the application cases were performed with limited datasets and showed some limitations of the approach that are described in the following.

First, the case studies are limited to the examination of a single building level. Due to the case study data sets, an inventorying to a building equipment connection port in a different story was not possible. Here, in future work extension is necessary to multiple stories combined with the respective information regarding central or decentral heating or power system and its piping or wiring from the level to the building port. However, this extension will not change model results.

Second, although the problem size seems relatively small, the case study 1 problem was not solvable for a time slice of five minutes due to an out-of-memory error in scenario 27 due to the large model decision matrices and model size (>> 6 GB). Although the project sizes do not seem very large, both case study problems created large decision matrices of [1552 x 8100] rows and columns with about 1.4 million decision variables in case study 1 and [7379 x 77562] rows and columns with about 572 million decision variables in case study 2[27]. For larger problem sizes, the time granularity has to be further reduced to ensure solvability. This comes along with a decreased differentiation of the activity durations and thus a more inaccurate schedule and resource assignment. The tests during model development and also the presented case studies

[27] See section 4.4.1 for the determination of the matrix sizes.

showed, that the number of time slices or project makespan (T_J) has a great influence on the computational effort and run times. Thus, to decrease run times, the reduction of time slices (granularity) in the model decreases running times dramatically. Also, hazardous materials (asbestos, wood preservatives (DDT, Lindan, PCP), synthetic mineral fibers (KMF), polychlorinated biphenyl (PCB), polychlorinated aromatic hydrocarbons (PAK)) were integrated into the model. But, then the activity durations greatly vary and partly lead to considerably larger decision matrices so that the scheduling of the problem is not possible anymore or the problem is only solvable at the cost of considerably coarser time slices. Due to the complexity of the topic of hazardous and harmful substances in buildings, other substances such as dissolver in paints/coatings, epoxy resins, isocyanides, formaldehyde, bitumen, separating agents/forming oils, chromate (in cement) and organic compounds (Kohler et al. 1999 p. 13) have not been considered in this research contribution but might be subject to future research and model extensions.

Third, in contrast to other works, such as of (Akbarnezhad et al. 2014) or (Cheng and Ma 2012) that need a preexisting Building Information Model (BIM) as data input, the model of this research contribution can process pre-processed building information based on sensor data and user inputs that are easier to generate onsite during building site inspection and require much less manual modelling effort. However, as discussed before the developed model does not include current BIM or IFC standards but follows the German DIN276 classification of building elements and the respective hierarchical building element structure. However, as the model is programmed in an object-oriented way, future research is needed to implement a respective data interface. However, the presented case studies showed that the processing of the sensor data and the building inventorying could be helpful and timesaving tool to generate building inventories in practice. But, as currently the calculation of GFA and GV follows a triangulation function, case study 2 showed that this does not calculate the exact GFA and GV values as defined in

DIN 277-1:2005-02 due to the protrusions of the patients' bathrooms. In further research, the GFA and GV calculation might be further enhanced via specifically adapted triangulations or sophisticated calculations of complex contours and enveloping functions of buildings' ground floor areas.
Forth, the recovery cost value calculated by the model can increase the comparability of recovery costs between various deconstruction and recovery projects and the current raw material price. However, as it is only calculated per material, the recycling revenues of other materials are not considered. And, as the recycling and disposal fractions are only assumed depending on their material, and the local and regional recycling options on near construction sites often are not known due to a structural information deficit, the identified recycling and disposal rates do not necessarily reflect the real values.

6 Conclusions, discussion and outlook

This chapter summarizes and concludes the findings and results of the research contribution at hand. Also, a discussion of the developed approach and the implemented model is presented. Finally, an outlook on future research is given.

6.1 Summary and conclusions

This research answers the research question of how the selective deconstruction of a specific building can be robustly planned under technical and spatial restrictions and uncertainty. Aim of this work was the development and implementation of a project planning and decision support model to robustly plan building deconstruction projects that are subject to uncertainty and that enables and facilitates decision support under uncertainty. For that purpose, in this research contribution an operative deconstruction project planning and decision support model was developed and implemented. The proposed model enables the planning of a single deconstruction project with a high level of detail and the consideration of uncertainty, information updates and decision makers risk preferences under given technical and spatial constraints.

In this research contribution, chapter 2 provides and overview on deconstruction projects framework conditions. However, an analysis of the current project framework conditions in chapter 2 reveals that there is a vast amount of legal regulations in place regulating the material separation, the material transportation, the recycling and disposal of mineral and non-mineral C&D waste. Main characteristics of deconstruction projects are their time and cost pressure, and models based on buildings physics are adequate to depict the technical and spatial restrictions or deconstruction projects. But, it also becomes obvious, that the information management in existing buildings and consequently also the project planning database in deconstruction projects is suboptimal and requires a flexible and robust project planning and project management handling uncertainties. Thus, chapter 2 answers the first sub research question of the current project conditions in the deconstruction industry.

Chapter 3 reviews general and specific project management approaches and analyses their suitability for deconstruction project planning. Building deconstruction processes are organized in projects and are subject to time, cost, resource and space constraints as well as uncertainty. Thus, methods of project scheduling and capacity planning with consideration of uncertainties can be applied to robustly plan deconstruction projects. The general and specific project scheduling literature in chapter 3 showed that current approaches focus on deterministic deconstruction planning but neglect uncertainties, information updates during project execution, robustness and decision makers' preferences. Due to often lacking building information of existing structures in question (Volk et al. 2014), consideration of uncertainties seem to be the most pressing issue in this field, rather than further detailing and constraining the existing deterministic approach of (Schultmann and Rentz 2001). Thus, chapter 3 answers the sub questions of what suitable project management approaches are that are able to include uncertainty that occur in deconstruction projects.

Chapter 4 formulates a robust deconstruction project planning model with inventorying functionality, scenario construction and a scheduling and capacity planning model part under and time, cost and technical constraints. Also, the developed model includes uncertainties and can include expert estimations. And, the current robust baseline schedule can be adapted or changed if new information arises and the previous schedule becomes infeasible. Due to the scenario construction, main results are the now possible identification, integration and quantification of uncertainties for building deconstruction planning. Moreover, risk preferences of decision makers (here: deconstruction, remediation and recycling companies, assessors/consultants) are addressed and included in the developed decision support model. It could be demonstrated that the inclusion of uncertainties and the consideration of decision makers' risk preferences have an impact on project scheduling and resource assignments, as it leads to other preferred deconstruction schedules and strategies than in the deterministic case. Depending from the risk preference of the decision maker or model user, planning strategies and potential financial consequences might differ (e.g. due to contractual penalties, application of other techniques or preventive measures). The model provides a sounder basis of decision making in deconstruction projects for the mentioned potential users. Thus, chapter 4 answers the research questions of what type of uncertainties occur in deconstruction project, it provides an approach of how these uncertainties can be integrated into deconstruction project planning and it quantifies the impacts of uncertainties on project planning.

Chapter 5 exemplary demonstrates the deconstruction project planning and decision support model application in two case studies of a residential and a non-residential building part. The developed model allows the decision maker to compare alternative deconstruction scenarios and alternative deconstruction strategies with respect to their total project makespan and their expected cost. This shows a range of possible project outcomes and it allows the quantification of the risk inherent in the potentially varying building configuration and resource productivity. The application cases show that the developed approach and the realized model are working for different datasets and for different parameter constellations of the generated scenarios and also of user inputs (such as resource capacities). Compared with the deterministic case of both case studies, it can be stated that in both case studies the model recommends robust deconstruction strategies to the user that differ from the optimum deconstruction strategy in the deterministic case. Furthermore, the

application cases and their verification indicate that the developed model provides reasonable and plausible material masses when compared to literature values (see verification sections 5.1.6 and 5.2.5). Also, in case study 1 the calculated project cost is in a realistic range (see sections 5.1.6).
However, the model application also showed that the model size increases dramatically and also the computational effort rises with the number of activities and the number of time slices (see also discussion on model granularity in section 6.2). As the deconstruction project planning and compilation of bidding documents sums up to about 2 hours in practice, the models' computation time of about 75 minutes fits well into the current timeframe in practice. Furthermore, the case studies show that the approach is intuitive and easy understandable to model users which might lead to a high acceptance in practice. Here, it might be helpful that only a small group of model users is to be convinced (Bartels 2009 p. 114) and that the software integration to currently used PM systems e.g. via MS Excel would be easy to implement. With respect to application considerations, the specializing of the model in older buildings and privately owned buildings seems promising, where the data situation and building documentation is particularly bad (Kohler et al. 1999 p. 6).

6.2 Discussion and critical appraisal

In this subsection, the developed deconstruction planning and decision support model is critically discussed and model limitations are demonstrated. Detailed discussions can also be found in section 4.7.2 and section 5.3. Therefore, in the following this section focuses on the most relevant aspects of model granularity, system boundaries, model structure, used data and uncertainties as key aspects with respect to the research question.

6.2.1 Model granularity

The proposed model tries to depict deconstruction projects as realistically as possible. However, to obtain an as detailed model as possible and at the same time a fast solving decision support model, a tradeoff has to be made which is associated with simplifications and a certain granularity or level of detail (LoD). In this model, model granularity is mainly defined by the main model parameters of time slices and activities' aggregation to deconstruction activity sets. The resulting tradeoff can be criticized as it strongly influences model results and the representation of uncertainties in the model. The automated definition of appropriate time slices was tested, however not optimal result or way of modeling was found as this model parameter is very dependent on the project size (number of building elements, duration of deconstruction activities). Thus, this parameter has to be manually changed by the user (in the program code), but it is at the same time very influential on model solutions and model computing times. In this model, we proposed and implemented four different kinds of activity aggregation (no aggregation, aggregation according to unique building element types and rooms, aggregation according to trades and rooms and aggregation to unique building element types) into activity sets which influence model size and location-demand, if the activities are grouped over several locations (e.g. rooms). Here, the aggregation according to trades and rooms is chosen. However, it might be too detailed or too aggregated when it comes to project planning of larger or smaller deconstruction projects.

6.2.2 System boundaries

Currently, the developed model has some restrictions that might lead to an unrealistic representation of deconstruction projects and their conditions.

First, the number of scenarios is limited to 27, as it results from the variation of three parameters by 3^3 and in the model not all existing uncertainties are considered. However, if further influencing building-related uncertainties are identified that have to be considered, the scenario construction can easily be extended by a variation of this additional uncertain parameter. The scenario construction only includes foreseeable uncertainty. Resource unavailability is regarded as unforeseen uncertainty. However, if uncertain resource capacities or availabilities during project execution would be considered and included in the model by additional scenarios, the number of scenarios would increase dramatically due to combinatorial explosion, so that computation time would exceed project planning time.

Second, the model aims at minimization of the project makespan. Other objectives are not considered here. Project costs are a resulting value from makespan minimization. As already discussed in (Schultmann 1998 p. 123), the project makespan minimization can be used as a substitute for cost minimization.

Third, the model is limited to deconstruction activities. Separation, sorting, processing, loading, transportation, recycling or disposal activities are not included yet. The modeling of these activities might have a differing effect, depending on the building type and the predominant material. For example, necessary masonry processing effort of crushing or shredding is done with a sorting grab and is rather low, while crushing and processing of reinforced concrete is associated with high effort (Lippok and Korth 2007 p. 352). As these activities are not yet included, this might lead to an underestimation of total project time and cost. However, if necessary these activities can be easily included in the model.

Fourth, the implemented building inventorying model part is expecting rectangular or straight building elements of the main structural elements such as ceilings, floors and walls. Round, bowed or organically shaped structural building elements cannot be processed by the model yet. And, the buildings' statics (e.g. of vertical placement of walls above each other) are not considered and evaluated yet as well as their implications on project planning and additional project activities such as protective or securing measures. This constitutes a promising field of future research.

6.2.3 Model structure

This section describes what impacts the chosen modeling approach has on the results.

First, as a binary multi-mode resource constrained project scheduling problem is modeled, continuous resources cannot be represented by the model. This especially affects resources representing container and storage capacities which cannot continuously filled by deconstruction or loading activities.

Also, further technical restrictions such as maximum operating height or maximum building element thicknesses suitable for resources might additionally by included in the model. However, these extensions might reduce the solution space but might better reflect site conditions and technical constraints. Furthermore, in practice, the buildings' supporting structure is deconstructed laterally and from above simultaneously. However, this is difficult to model in automatically derived precedence relations, as it (the starting and ending point of the lateral deconstruction) is often dependent on the building site and the available space onsite. But, as this only affects the building structure (walls, ceilings, floor, without foundation), for simplicity the level-wise deconstruction can be assumed as in (Schultmann 1998 p. 188) and as described in section 2.3.5.2.

Second, non-preemptive activities are modeled and the splitting or preemption of activities is not possible in the model. Preemptive jobs are not considered, which might influence the schedule in the case, that when something unexpected is found, usually all further activities are stopped to examine the found issue, sample and evaluate it (and get authorities approval) before returning to the preempted and next activities. And, if an information update arises in that leads to schedule changes, an activity might be interrupted by that information update. Currently, if the new robust deconstruction strategy is not determined by rescheduling, the only entire activities are considered and already started activities are neglected by the calculation of project makespan, cost and robustness criteria.

Third, statements on the time-resource, time-cost or cost-resource tradeoffs are not possible as the model minimizes project makespan and assigns activity modes and resources respectively. Furthermore, statements on the optimal degree of deconstruction are also not possible as the degree is predefined by the number and type of activities that are derived from the building elements. In this approach, only a single deconstruction activity is derived per building element, but can be easily extended to the proposed six activity types in section 4.4.1.

Forth, due to the currently implemented model structure the resulting schedule is not timetabled onto working days or weekends or staffs' vacations.

Fifth, currently an exact model solver is used to solve the MRCPSP. However, when the model is applied to large projects with a high granularity, the resulting large problems could not be solved by exact methods (Xu and Feng 2014). Thus, for large deconstruction projects such as nuclear power plants, other solving methods such as decomposition approaches or heuristics have to be applied to reduce problem size or to fasten the solution process. However, the applied heuristics might not provide globally optimal but locally optimal solutions.

6.2.4 Used data

The used data that is underlying model calculations is based on literature, standards and experts' experience values. A large majority of building inventorying data and parameters is imported via MS Excel files or can be easily modified in a graphical user interface. Reinforcement values are assumed to be homogeneous in foundation, floor and ceiling slabs as well as in walls. However, in reality structural reinforcements might be inhomogeneously distributed in ceiling slabs, floor slabs and foundations e.g. due to punctual impact points of pillars. Thus, the reinforcement values might be further detailed by exact structural analysis and reinforcement bar placements (e.g. increased reinforcements under pillars for avoiding breakthrough). Furthermore, modeled activity types and modes, resources, building elements and their properties (e.g. materials) are modeled in a simplified way to demonstrate the model functionality. The chosen activity types and modes, resources, building elements and element properties are able to describe the key building elements and activities in building deconstruction, but can be further detailed in future to model deconstruction projects more realistically. However, this will be associated with a higher computational effort and might lead to insolvability.

As there are no experience values and data available regarding the occurrence of certain (hazardous) materials or building elements, no scenario probabilities are available. Scenario probabilities are also not considered in the case studies. Maybe in other cases the probabilities are known or can be subjectively approximated by experience. Then, the selection and weighting of scenarios might strongly influence the model results and the chosen deconstruction strategy by the given or assumed probability. Nevertheless, the consideration of the base, best and worst case scenarios provide insight on the potential risk (time lag) that is associated with the potential project realizations. However, in the case of frequent model use, an experience database could be established and with a certain number of projects, probability distributions of materials and building elements occurrence as well as of scenarios could be derived.

And, the model was tested only with a limited amount of cases including a limited number of building types, building element types and building element properties. Possibly, for application and practice and other building types (especially non-residential and industrial buildings such as storage halls, productions sites and facilities) further testing is needed and the necessary data might not yet be included in the default values of the model.

6.2.5 Uncertainties

The uncertainty classifications used in this paper might not include all pertaining uncertainties and not all project risks might be considered in this model. But, the current scenario construction is seen to be sufficient to depict major foreseeable uncertainties related to building deconstruction projects. But, the created scenarios may not reflect uncertainties adequately and might not capture the essential / relevant scenarios. General external uncertainties and unforeseeable project risks and uncertainties are not modeled here yet and are far more difficult to quantify and to include into project planning. Those uncertainties might be included by other general project management approaches such as PMBoK.

And, the relevant strategic or financial risks for deconstruction companies that result from the specific operational risks of single deconstruction projects are not considered here. For this purpose, an extension to a multi-project approach would be necessary to overcome this and to answer operational questions on the project portfolio risks.

As there are still model and data uncertainties in the proposed deconstruction project planning and decision support model, the model results have to be seen as recommendations with these limitations in mind and might still underlie the necessity of manual model result changes and project schedule modifications by the user.

6.3 Outlook on future research

In this section, based on the previous discussion of this research contribution, an outlook on future research is given together with potential model extensions. This section focuses on the most relevant aspects of improvement of model data, extension of system boundaries, transferability to other potential application areas and inclusion of stakeholders.

6.3.1 Improvement of model data

Future research can be devoted to a further detailing of the model granularity and the model data to increase the model accuracy. This might focus on the explicit anticipation of time and cost increases caused by sample testing, preventive measures, choice of technology, process lags, ready and idle times, contractual penalties, quality reductions in recycling materials. But this might also include the increase of scenarios or another way of modeling uncertainty of activity duration and cost or resource unavailabilities (fuzzy or stochastic) in the model. "Program Evaluation and Review Technique (PERT) is an effective method of considering risks in a project time-wise. It is highly effective when used in conjunction with the Monte Carlo model and combined with Statistics Gauss Probability Distribution to find either, the probability of [project] completion when there is a certain time available for the project or the time needed to get a pre-established probability of completion." (Munier 2014 p. 21). In future, probabilities of activity durations, cost, building element and material compositions or building constructions could be determined by surveys, measurements or frequent application of the ResourceApp system or similar building audits and the establishment of an experience database especially of time and cost estimates. These repeated "snapshots" and their analysis might provide insight on the typical building configuration and project situation (Reuter 2013) and further enhance the model either by scenario probabilities or by stochastic scheduling. According to DIN 6 9901-3:2009-01, 4.3.2 at least 10 to 30 projects are required for such a database, except for very similar projects where a lower number of projects is also valid. At the moment, probability data on buildings and deconstruction activities are not sufficient for a stochastic scheduling optimization.

Another promising detailing of the model might focus on older buildings where the data situation is particularly bad (Kohler et al. 1999 p. 6). Also, the extension of the inventory model part by GIS-based data for documentation or retrofit applications might be promising to receive a spatially resolved material cadaster and register of hazardous substances like proposed in (Rechberger and Clement 2011). Due to the novel approach in this research contribution and the complexity of the decision making in deconstruction projects, residential buildings (single family and multi-family houses) with relatively simple configurations and structures are focus of this work. Nevertheless, an extension of the here presented approach to other building types of residential accommodation or to non-residential buildings (e.g. educational, commercial, office or administrational buildings) could be promising (see also section 2.1.1).

6.3.2 Extension of system boundaries

Extensions of the system boundaries might include sensors to detect hazardous materials and building elements and their information that could be integrated into the robust project planning system. Although there is many literature available regarding hazardous building elements and materials as well as the main periods of insertion (see Appendix I) and (Berg et al. 2014; Rötzel 2009; Schultmann et al. 1997; Zwiener 1997), the reasoning or determination of probability of the occurrence hazardous materials is not possible due to incomplete building documentation regarding original building elements and all retrofitting measures.

Furthermore, rapid developments in recent years dramatically changed the possibilities of construction project management, building information management and documentation. Since the year 2000, digital building information models (BIM) are increasingly used to plan and execute new construction projects but also to manage and maintain buildings (Volk et al. 2014). And, BIM and other digital planning, surveying and controlling tools in the construction industry are getting obligatory in many countries for new construction e.g. USA, Norway, Finland, Denmark and Great Britain for public construction projects. Due to digital documentation of building information and sustainability information (e.g. material demand, deconstruction and recycling information) in the last two decades in CAD, BIM, LCA and environmental product declarations (EPD), it becomes necessary to processing this building information to use them in retrofitting, remediation or deconstruction projects. Moreover, project tracking and controlling[1] methods and adaption techniques on new requirements or project dates of construction industry e.g. by live monitoring of the construction site with image recognition and automated information and schedule updates or rescheduling or modelling, visualization of environmentally friendly dismantling and recycling (Liu et al. 2003) or performance monitoring indicators (e.g. earned value management (EVM) (Munier 2014 p. 4)) are promising for future extensions and research. An IFC or BIM interface of the proposed system might support the pending digitalization of retrofit and deconstruction projects and related processes in C&D industry and will also become relevant for the deconstruction industry in the next decade.

Additionally, the integration of external risks might be promising to further research the vulnerability, dependency and robustness of project resources and the extent of damage of deconstruction projects. Because, information on vulnerability can make a contribution to evaluation and mitigation of risks (Merz 2011 p. 14) and might help to establish a risk database (comparable to the one used in (Schatteman et al. 2008) for construction projects) for deconstruction projects. Future research might examine and evaluate past risks with respect to their effect on project activities, durations, resource availability etc. This might result in the extension to a learning system that automatically updates the risk evaluation of future projects' planning (e.g. by additional scenarios or if possible by an information on the probability of occurrence). This might be especially interesting for the planning and management of large deconstruction projects such as nuclear facilities and their risk management.

[1] For controlling methods and indicators see e.g. DIN 69901-3:2009-01, 4.2 or (Kenley and Seppänen 2010).

For further integration of uncertainties in deconstruction planning, the testing of (baseline) schedules under external stress of disturbing or interruptive events can be further examined like in (Rasconi et al. 2010). Then, the impact on project planning could be simulated and a further protection of the deconstruction schedules against worst-case events or most probable disturbing events could be included. This would lead to further research efforts in dynamic project planning.

And, the model might be extended to a multi-project model (e.g. similar to the model formulation in (Sunke 2009 p. 67) for construction projects) that allows decision makers to analyze and evaluate resource allocation on the whole project portfolio via portfolio analyses based on decision makers' risk preferences.

In several countries like Switzerland or Austria waste regulations are strict and expected to be further restricted in Germany and other countries in the next years, e.g. in Germany in the course of the planned and discussed Mantelverordnung (MantelV). With respect to the waste management in deconstruction projects, the proposed model could be further extended to include predefined recycling targets or recycling rate maximization for the further closing of material cycles and to address environmental impact assessments or other evaluations of the generated raw materials and products in deconstruction projects. Apart from that, the trend to product stewardship of producers (e.g. in Germany for packaging materials, batteries, electrical appliances, mobile phones or cars) might provide further recycling options for building materials and elements in future. Few examples in this area for PVC window frames, PVC pipes and PVC floor coverings are outlined by (Lippok and Korth 2007 p. 445).

6.3.3 Transferability to other potential application areas and inclusion of stakeholders

Due to the development of Germany's building stock and the demographic developments from rural to urban areas, retrofitting, decon-

struction and remediation of the numerous buildings of the decades 1950-1980 is a major issue. The increase of material variety, (potentially) hazardous substances and technical equipment in newer buildings is challenging. Moreover, the constant increase of energetic, climatic and indoor-air requirements of buildings will lead to further retrofitting, remediation and deconstruction (and subsequent newly built substitutes). The extension of the proposed decision support model to retrofit and remediation projects under uncertainty (eventually based on BIM and its building element/component libraries) is a very promising field of research. First works in the retrofitting decision support demonstrate the need for future research, e.g. (Menassa 2011) with a qualitative investment evaluation, (Donath et al. 2010) with a deterministic building model and retrofit planning approach or (Rysanek and Choudhary 2013) with an approach under technical and economic uncertainty and decision making with risk preferences.
As discussed before, the transferability of the proposed approach to the project planning of large deconstruction project such as the deconstruction of complex nuclear power plants and facilities is theoretically possible. However, as these facilities are associated with a high number of project activities and a long project makespan, a high number of stakeholders and high risks, uncertainties and safety requirements, respective adaptions have to be made. Extensions to plan the deconstruction of infrastructures does not seem reasonable due to the different structures, structure elements and materials that would require a very high adaptation effort. (Large) deconstruction projects also face a number of involved stakeholders that are not yet explicitly considered in project planning models In deconstruction projects, the integration of lean construction techniques to improve project organization are not explicitly applied but might reduce project makespan (Issa 2013). Thus, the integration of lean construction techniques into deconstruction project plans and decision making especially in large deconstruction projects might be promising, when planning of permits or sampling and coordination of numerous stakeholders are getting challenging.

7 Summary

In recent years, increased research efforts in robust optimization and robust planning and scheduling approaches have been made, motivated by the shortcomings of deterministic project planning approaches. To plan projects, methods of operations research are applied to schedule project activities and resources and to confine project plans to time and resource constraints.

During their lifecycles, buildings are modified when different building elements and products are installed, removed or changed. In addition, some buildings cannot be economically adapted to changing requirements and consequently are deconstructed. The buildings in question undergo deconstruction (and replacement) processes, often in spatially limited sites of dense urban areas, with limited resources available and under high time and cost pressure. Therefore, the objective of the responsible decision makers in deconstruction projects is either makespan or cost minimization or both, depending on the building type and the preference of the decision maker.

Deconstruction projects are projects under uncertainty and main characteristics of deconstruction projects are time and cost pressure and relative short project durations (days, weeks or few months) depending on the object size. The deconstruction of larger structures such as large buildings, infrastructures, or nuclear power plants might take years or decades and is also subject to considerable uncertainty.

With respect to deconstruction project planning, in many existing buildings, incomplete, obsolete or fragmented building information is predominating (Becerik-Gerber et al. 2012; Gursel et al. 2009) and result in partly unknown or uncertain building configurations and planning uncertainty. Today manual building auditing is based on subjective notes taken during onsite inspections, depending on the inspectors' knowledge, experience and available time. This suboptimal information management

in deconstruction objects and projects has to be considered in project planning methods. Exact mass calculation often requires a very high effort (Lippok and Korth 2007 p. 117ff.). Thus, often simplifications and assumptions (e.g. on gross volume or percental material masses of the building) are used as a basis for project planning and decision making.
This results in higher planning risk based on deviations from estimated mass and material values and might lead to inadequate judgments (Lippok and Korth 2007 p. 117ff.). Thus, deconstruction project planning without the consideration of uncertainty might lead to unexpected project prolongations and cost overruns. Project makespan delays should be avoided as in most cases they induce considerable contractual penalties and further delays of subsequent activities and resource occupation and might lead to supplement offers, litigation or insolvency (Lippok and Korth 2007 p. 117ff.).
Currently, deconstruction projects are planned based on experience values and deterministic assumptions and planning approaches. In deconstruction project planning theory, project planning under certainty or fuzziness are used for that purpose. Scheduling applications in deconstruction projects are mainly limited to deterministic approaches yet (Schultmann 1998, 2003; Schultmann et al. 1997; Spengler 1998; Sunke 2009), that complement the original approach of (Schultmann 1998) by several extensions. Uncertainties modeled in RCPSP in other application contexts are numerous, but applied operations research methods considering uncertainties in building and infrastructure deconstruction project planning are limited to (Schultmann 2003; Schultmann and Rentz 2003).
The reviewed deconstruction project planning approaches do not consider all characteristics of deconstruction projects yet, such as (a) multi-project scheduling with multiple deconstruction sites from the contractors' perspective, or (b) multi-objective scheduling of deconstruction projects with minimum resource demand, robust schedule, maximum net present value or maximum quality level (e.g. recycling rate), or (c) locations and spatial restrictions, (d) information updates/changes and

uncertainties in the planning input information, or (e) flexible/dynamic project structure over time, or (f) risk management considering the decision makers preferences or (g) robust scheduling of deconstruction projects to generate reasonably good objective values despite changes in information, project status or resource constraints which have important practical implications.

In this research contribution, a project planning and decision making support model is developed for and applied in building deconstruction projects to identify and reduce risk and uncertainty in deconstruction project planning. The developed model analytically schedules project activities while taking into account the characteristics of deconstruction projects. In the research contribution, methods of operations research (OR), decision theory and scenario techniques are combined.

The model comprises four main model parts (A, B, C, and D). Part A includes a building inventorying method based on preprocessed sensor data and a scenario construction. Part B describes the deconstruction project scheduling with respect to time optimality. Part C treats the generation of deconstruction strategies and the robustness evaluation of these strategies. Part D includes information updates and project changes and their effect on decision making in deconstruction projects in a reactive model part.

Part A includes a building inventorying logic based on imported sensor information that is gathered during building site inspection and based on standards and literature. As the sensor captures interior building information from the indoor perspective, several building inventorying parameters have to be provided by the model, based on standards and literature. Then, occurring uncertainties in building auditing (building element-related) and deconstruction planning (activity-related) are systematically analyzed.

Based on the building inventory and to support decision makers in deconstruction project planning under uncertainty, a proactive scenario construction is developed (part A) that considers three main foreseeable uncertainties in deconstruction projects. First, these uncertainties include the building elements' materials which are decisive for the mode selection and resource assignment of the project activities. Second, building element volumes are uncertain as building documentation is often fragmentary or does not represent the as-built condition of the building. Third, duration coefficients of deconstruction activities might vary due to different resource productivity. All three types of uncertainties in deconstruction projects are foreseeable uncertainties that impact activity durations and are modeled in scenarios. Although risks in deconstruction projects can often hardly be quantified, the proposed approach offers a method to calculate potential impacts of several, main uncertainties in deconstruction projects and thus to quantify their risk (impact on project time and cost).

Model part B shows how deconstruction activities are derived from the different, generated scenarios and their building inventories of model part A for the deconstruction project in question. In the model, the user is able to define the grouping of deconstruction activities to activity sets of common deconstruction works and to automatically generate the specific precedence relations of all deconstruction activities in the project. For this purpose, the model provides four different activity grouping options. Then, for each scenario, a time-optimal project plan (schedule) and deconstruction strategy (sequence) is calculated in a multi-mode, time- and resource-constrained capacity project scheduling problem (MRCPSP) with constrained resources and locations onsite (part B). The MRCPSP is considering multiple execution modes as alternative deconstruction activity techniques with different resource demands and costs. Resource capacities are met in MRCPSP during the whole project makespan. Based on the optimal solution per scenario, total project costs are calculated. Here, for the first time, the MRCPSP was extended to onsite locations. Locations are modeled as renewable resources that are subject to further location-specific constraints where parallel works in the same locations are excluded. This secures that activities are not planned at the same time and location, so that staff safety and logistic aspects are respected.

Part C describes the transformation of the optimum deconstruction schedules in each scenario into deconstruction strategies and their robustness evaluation. In deconstruction contexts, rather risk-averse risk preferences of decision makers' are considered in this approach. And, the objective value of the total project makespan is considered the main decision criterion. Thus, the generated deconstruction strategies are selected according to the optimality-robust measure of the minimum average absoluteute regret with respect to the project makespan. To evaluate the deconstruction strategies performance in all scenarios, the generated deconstruction strategies representing the sequence of activities on the available resources are re-applied by a heuristic onto all scenarios. After this stress test of the deconstruction strategies and the evaluation of their robustness criteria, the most optimality-robust deconstruction strategy is identified. As the decision making based on risk attitudes is associated with a subjective uncertainty perception and risk assessment, sensitivity analyses are performed to examine their influence on model results and decision recommendations.

In part D, changing information on variable time instants during the project execution is integrated in the developed proactive planning approach of model parts A to C. Reactive model part D details the potential processes during project execution, when new information on the project status, the building elements, the resource capacities and other project parameter arise and change project conditions. In this model part, either a local search or a re-scheduling approach are proposed and described depending on the type of new information that arises during project execution and its impact on remaining activities and the baseline project schedule. This reactive procedure allows decision makers to change the original baseline schedule during project execution, but at the same time provides decision making support regarding the schedule change. The reactive procedure aims at finding a nearly as robust solution in the existing set of deconstruction strategies or creating a new deconstruction strategy for the remainder of the project.

The applicability and the decision making support of the developed model is illustrated by two case studies. The developed robust deconstruction project scheduling and decision support model is implemented as a program in MATLAB 2015b (64bit) in an object oriented manner. The main building elements and spaces are implemented in a hierarchical order of building, spaces and building elements. The model results are based on building data that can be automatically captured by sensor (CSV/OBJ interface). Other necessary data for the inventorying of the building elements and the project planning parameters are either imported from MS Excel or entered by the user in three consecutive graphical user interfaces realized in MATLAB.
Both case studies consider deconstruction project planning of two different building types (residential, non-residential) and project sizes with respect to the gross volume and the number of inherent building elements. Case study 1 focuses on the deconstruction project planning of a small single-family residential apartment with four rooms and solely electrical equipment. This case study is well-suited to demonstrate the model functionality and results in a comprehensible way. Case study 2 is a larger case study that generates a robust deconstruction project planning of a hospital part with thirty rooms (patient rooms, patient bathrooms, diagnosis and treatment rooms, staff rooms and aisle) and electrical, waste water and drinking water equipment as well as heating installations. This more complex building part demonstrates the applicability of the project planning and decision support model in larger, more realistic project circumstances.
The application cases show that the developed approach and the realized model are working for different datasets and for different parameter constellations of the generated scenarios and of user inputs (such as resource capacities). Furthermore, the application cases and their verifi-

cation indicate that the developed model provides reasonable and plausible material masses when compared to literature values (see section 5.1.6, case study 1) and to literature and measured values (see section 5.2.5, case study 2). Also, in case study 1 the calculated project costs are in a realistic range (see section 5.1.6). The tests during model development and the presented case studies showed that the number of time slices and the number of deconstruction activities (model granularity) have a great influence on the computational effort and run times.

The presented predictive-reactive (robust) scheduling approach for deconstruction projects is based on previous works of MRCPSP under uncertainty. The difference to known approaches is the strong relation to the presented application case in deconstruction projects, as well as the extension by a scenario construction to get more suitable activity durations, the consideration of locations in MRCPSP and integration of the optimality-robustness criterion. The proposed problem formulation and solution procedure follows a total planning approach (all activities are planned at once). However, due to potential future information updates only the short-term activities can be seen as compulsory, whereas the later planned activities can rather be considered provisional and can be changed by later incoming information. The proposed method belongs to the class of flexible project planning according to the definition of (Scholl et al. 2003 p. 12), as it generates baseline plans for several scenarios in each stage that might serve as alternative plans in the case of the realization of another scenario. But, it also belongs to the class of robust planning because of the selection of strategies (plans) according to a robustness criterion.

The main advantages of the presented individual, building-related approach on micro level lies in the high level of detail and thus expected realistic model results. The model allows decision makers to inventory buildings and to quantify material masses and recycling and waste fractions objectively. Also, the model allows a project scheduling optimization under consideration of uncertainty and the evaluation, comparison and selection of alternative project plans under different scenarios for different project framework conditions, which had not been possible before. The developed model enables decision-makers in deconstruction contexts like operators, planning engineers, architects and experts to robustly plan the resource allocation in deconstruction projects over the course of a deconstruction project and thus to reduce planning risk. Furthermore, locations are explicitly modeled as renewable resources in deconstruction project planning. This can help to avoid working team jamming and to improve onsite logistics of machinery, deconstructed material and building elements. Further benefits are the consideration of information updates, robustness and risks as well as hazardous materials into the planning with first priority in precedence relations (according to legal obligations in Germany). Furthermore, it allows a model user to select deconstruction strategies according to their risk preferences and to modify model parameters. Nowadays, deconstruction project scheduling is done manually which will not necessarily provide the optimum schedule or consider operational uncertainties and risks.

Altogether, the developed approach provides decision makers with an improved planning information base for building inventorying, project planning and controlling (re-planning) (which is crucial in time (or cost) controlled industries like the (de-)construction industry) and has an appropriate compromise between planning effort and planning quality. The proposed deconstruction project planning and decision support model improves the current deconstruction project planning and decision making where only a single deterministic case (eventually combined with a thumbs-rule risk surcharge) is calculated and planned without considering potential operational uncertainties, which often results in project delays or cost increases.

The research contribution at hand reveals the following major research directions: improvement of model data, extension of system boundaries, and inclusion of stakeholders.

Model data improvements should include the establishment of an experience database especially with time and cost estimates of deconstruction activities. This would allow the derivation of more reliable activity durations and cost, e.g. via probability distributions and would allow the application of dynamic or stochastic scheduling approaches. Additionally, the integration of external risks (e.g. of disruptive events) might be promising to further research the vulnerability, dependency and robustness of project resources, the project schedule and the extent of damage and to establish a risk database for deconstruction projects that would allow a comprehensive risk management of these projects.

The system boundaries could be extended in several ways: First, additional sensors to detect (hazardous) materials automatically could improve model performance. Second, the adapation of BIM of IFC standards and respectively the development of an adequate interface could be promising, especially when the proposed model is further developed for retrofit project planning. Moreover, project tracking and controlling methods and adaptation techniques (to new project framework conditions) of construction industry are promising for future extensions and research e.g. by performance indicators or live monitoring of the construction site with image recognition and automated information and schedule updates, rescheduling, or visualization of environmentally friendly dismantling and recycling. Also, further detailing of the model granularity and further testing and model calibration could enhance model results and computational performance.

(Large) deconstruction projects also face a number of involved stakeholders that are not yet explicitly considered in project planning models. In deconstruction projects, the integration of lean construction techniques to improve project organization is not applied yet, but might reduce project makespan (Issa 2013). Thus, the integration of lean construction techniques into planning and decision making of especially large deconstruction project might be promising, when planning of permits or sampling and coordination of numerous stakeholders is challenging.

Appendix

Appendix I: Hazardous material introduction periods

Table 7-1: Exemplary listing of most important hazardous materials in building elements and materials according to their period of use in building construction in Germany[1]

Hazardous material	Building element	Material	Period of use	
			Beginning	End
Asbestos/ asbestos-containing materials	Asbestos cement in external wall cladding/covering (Wall)	Masonry, Timber, concrete, pre-cast reinforced concrete	1930	1993
	Floor covering (Slab)	(pre-cast) reinforced concrete, timber	1930	1993
	Asbestos cement in roof covering (Roof)	Timber	1930	1993
Chemical wood preservative Lindan	Wall cladding/covering (Wall)	Timber	1942	1990
	Ceiling cladding/covering (Slab)	Timber	1942	1990
	Roof truss (Roof)	Timber	1942	1990
Chemical wood preservative DDT	Wall cladding/covering (Wall)	Timber	1940	1972
	Ceiling cladding/covering (Slab)	Timber	1940	1972
	Roof truss (Roof)	Timber	1940	1972
Chemical wood preservative PCP	Wall cladding/covering (Wall)	Timber	1940	1989
	Ceiling cladding/covering (Slab)	Timber	1940	1989
	Roof truss (Roof)	Timber	1940	1989
Synthetic mineral fibers (KMF)	Wall insulation, non-bearing interior wall (Wall)	Masonry, Timber, concrete, pre-cast reinforced concrete	1900	2000
	Suspended ceiling (Slab)	(pre-cast) reinforced concrete, Timber	1900	2000
	Roof insulation (Roof)	Timber	1900	2000

[1] According to (DBU 2014).

Polycyclic aromatic hydrocarbons (PAH)	Parquet adhesive (slab)	(pre-cast) reinforced concrete, Timber	1800	1995
	Sealant (wall)	Masonry	1800	1962
Polychlorinated biphenyl (PCB)	Sealant (wall)	Masonry	1929	1999

Appendix II: European Waste Catalogue – Deconstruction Waste

Table 7-2: European Waste Catalogue (EWC) for construction and deconstruction wastes (Section 17)[2]

17 01 Concrete, bricks, tiles and ceramics	
17 01 01	Concrete
17 01 02	Bricks
17 01 03	Tiles and ceramics
17 01 06*	Concrete, bricks, tiles and ceramics containing dangerous substances
17 01 07	Concrete, bricks, tiles and ceramics , other than those mentioned in 17 01 06
17 02 Wood, glass and plastic	
17 02 01	Wood
17 02 02	Glass
17 02 03	Plastic
17 02 04*	Wood, glass and plastic containing or contaminated with dangerous substances
17 03 Bituminous mixtures, coal tar and tarred products	
17 03 01*	**Bituminous mixtures** containing coal tar
17 03 02	**Bituminous mixtures** containing other than those mentioned in 17 03 01
17 03 03*	Coal tar and tarred products
17 04 Metals (including their alloys)	
17 04 01	Copper, bronze, brass
17 04 02	Aluminum
17 04 03	Lead
17 04 04	Zinc
17 04 05	Iron and steel
17 04 06	Tin
17 04 07	Mixed metals

[2] (http://www.statistikportal.de/statistik-portal/Abfallkatalog.pdf), accessed: 24.2.2015.

17 04 09*	Metal waste contaminated with dangerous substances
17 04 10*	Cables containing oil, coal tar and other dangerous substances
17 04 11	Cables other than those mentioned in 17 04 10
17 05 soil (including excavated soil from contaminated sites), stones and dredging spoil	
17 05 03*	Soil and stones containing dangerous substances
17 05 04	Soil and stones other than those mentioned in 17 05 03
17 05 05*	Dredging spoil containing dangerous substances
17 05 06	Dredging spoil other than those mentioned in 17 05 05
17 05 07*	Track ballast containing dangerous substances
17 05 08	Track ballast other than those mentioned in 17 05 07
17 06 Insulation materials and asbestos-containing construction materials	
17 06 01*	Insulation materials containing asbestos
17 06 03*	Other Insulation materials consisting of or containing dangerous substances
17 06 04	Insulation materials other than those mentioned in 17 06 01 and 17 06 03
17 06 05*	Construction materials containing asbestos
17 08 Gypsum-based construction material	
17 08 01*	Gypsum-based construction materials contaminated with dangerous substances
17 08 02	Gypsum-based construction material other than those mentioned in 17 08 01
17 09 Other construction and demolition waste	
17 09 01*	construction and demolition wastes containing mercury
17 09 02*	construction and demolition wastes containing PCB (e.g. PCB-containing sealants, PCB-containing resin-based floorings, PCB-containing sealed glazing units, PCB-containing capacitors)
17 09 03*	Other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04	Mixed construction and demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

Appendix III: CSV/OBJ interface structure with data for case study 1

Table 7-3: CSV interface structure (GeoRefType=f (face) or v (vertice), Parent = Room number (for wall, ceiling, floor) or wall number (for outlets, lamps etc.)) with data for case study 1

ID	Building element type	GeoRefType	GeoRef	Parent	Building element material
1	Ceiling	f	1	1	Timber
2	Floor	f	2	1	Timber
3	Wall	f	3	1	Cellular Concrete
4	Wall	f	4	1	Cellular Concrete
5	Wall	f	5	1	Cellular Concrete
6	Wall	f	6	1	Cellular Concrete
7	Ceiling	f	7	2	Timber
8	Floor	f	8	2	Reinforced Concrete
9	Wall	f	9	2	Cellular Concrete
10	Wall	f	10	2	Cellular Concrete
11	Wall	f	11	2	Cellular Concrete
12	Wall	f	12	2	Cellular Concrete
13	Ceiling	f	13	3	Timber
14	Floor	f	14	3	Reinforced Concrete
15	Wall	f	15	3	Cellular Concrete
16	Wall	f	16	3	Cellular Concrete
17	Wall	f	17	3	Cellular Concrete
18	Wall	f	18	3	Cellular Concrete
19	Ceiling	f	19	4	Timber
20	Floor	f	20	4	Reinforced Concrete
21	Wall	f	21	4	Cellular Concrete
22	Wall	f	22	4	Cellular Concrete
23	Wall	f	23	4	Cellular Concrete
24	Wall	f	24	4	Cellular Concrete
25	Door	f	25	21	Timber
26	Door	f	26	22	Timber
27	Window	f	27	24	Timber
28	Door	f	28	17	Timber
29	Door	f	29	16	Timber
30	Window	f	30	38	Timber
31	Door	f	31	12	Timber
32	Window	f	32	11	Timber
33	Door	f	33	6	Timber
34	Door	f	34	3	Timber
35	Window	f	35	4	Timber

36	Socket	v	141	4	PVC
37	Socket	v	142	17	PVC
38	Socket	v	143	16	PVC
39	Socket	v	144	23	PVC
40	Socket	v	145	15	PVC
41	Socket	v	146	11	PVC
42	Socket	v	147	3	PVC
43	Switch	v	148	16	PVC
44	DistributionBox	v	149	3	PVC
45	DistributionBox	v	150	16	PVC
46	DistributionBox	v	151	21	PVC
47	DistributionBox	v	152	12	PVC
48	DistributionBoxFlat	v	153	3	PVC
49	DistributionBoxBuilding	v	154	3	PVC

Table 7-4: OBJ interface structure for vertices (v) with (x,y,z)-coordinates of both facial and vertex building elements for case study 1

Ref	Geo-RefType	X	Y	Z	Ref	Geo-RefType	X	Y	Z
1	v	0.00000	6.89120	2.60000	78	v	8.00000	10.0000	0.00000
2	v	0.00000	0.00000	2.60000	79	v	3.03078	10.0000	0.00000
3	v	2.79078	0.00000	2.60000	80	v	3.03078	5.69314	0.00000
4	v	2.79078	6.89120	2.60000	81	v	3.03078	5.69314	0.00000
5	v	0.00000	6.89120	0.00000	82	v	0.00000	5.69314	0.00000
6	v	0.00000	0.00000	0.00000	83	v	0.00000	5.69314	2.60000
7	v	2.79078	0.00000	0.00000	84	v	3.03078	5.69314	2.60000
8	v	2.79078	6.89120	0.00000	85	v	3.03078	10.0000	0.00000
9	v	0.00000	0.00000	0.00000	86	v	3.03078	5.69314	0.00000
10	v	2.79078	0.00000	0.00000	87	v	3.03078	5.69314	2.60000
11	v	2.79078	0.00000	2.60000	88	v	3.03078	10.0000	2.60000
12	v	0.00000	0.00000	2.60000	89	v	8.00000	10.0000	0.00000
13	v	0.00000	6.89120	0.00000	90	v	3.03078	10.0000	0.00000
14	v	0.00000	0.00000	0.00000	91	v	3.03078	10.0000	2.60000
15	v	0.00000	0.00000	2.60000	92	v	8.00000	10.0000	2.60000
16	v	0.00000	6.89120	2.60000	93	v	8.00000	5.69314	0.00000
17	v	2.79078	6.89120	0.00000	94	v	8.00000	10.0000	0.00000
18	v	0.00000	6.89120	0.00000	95	v	8.00000	10.0000	2.60000
19	v	0.00000	6.89120	2.60000	96	v	8.00000	5.69314	2.60000
20	v	2.79078	6.89120	2.60000	97	v	5.35300	5.69314	0.00000
21	v	2.79078	0.00000	0.00000	98	v	5.35300	5.69314	1.80000
22	v	2.79078	6.89120	0.00000	99	v	6.15300	5.69314	1.80000
23	v	2.79078	6.89120	2.60000	100	v	6.15300	5.69314	0.00000
24	v	2.79078	0.00000	2.60000	101	v	3.03078	8.98870	1.80000

25	v	2.79078	7.13120	2.60000	102	v	3.03078	8.98870	0.00000
26	v	2.79078	10.0000	2.60000	103	v	3.03078	8.18870	0.00000
27	v	0.00000	10.0000	2.60000	104	v	3.03078	8.18870	1.80000
28	v	0.00000	7.13120	2.60000	105	v	8.00000	7.45176	1.89930
29	v	2.79078	7.13120	0.00000	106	v	8.00000	6.65176	1.89930
30	v	2.79078	10.0000	0.00000	107	v	8.00000	6.65176	0.79930
31	v	0.00000	10.0000	0.00000	108	v	8.00000	7.45176	0.79930
32	v	0.00000	7.13120	0.00000	109	v	6.15300	5.45314	1.80000
33	v	0.00000	7.13120	0.00000	110	v	5.35300	5.45314	1.80000
34	v	2.79078	7.13120	0.00000	111	v	5.35300	5.45314	0.00000
35	v	2.79078	7.13120	2.60000	112	v	6.15300	5.45314	0.00000
36	v	0.00000	7.13120	2.60000	113	v	3.03078	3.05787	0.00000
37	v	0.00000	10.0000	0.00000	114	v	3.03078	2.25787	0.00000
38	v	0.00000	7.13120	0.00000	115	v	3.03078	2.25787	1.80000
39	v	0.00000	7.13120	2.60000	116	v	3.03078	3.05787	1.80000
40	v	0.00000	10.0000	2.60000	117	v	8.00000	1.05035	1.89930
41	v	2.79078	10.0000	0.00000	118	v	8.00000	1.05035	0.79837
42	v	0.00000	10.0000	0.00000	119	v	8.00000	3.40035	0.79837
43	v	0.00000	10.0000	2.60000	120	v	8.00000	3.40035	1.89930
44	v	2.79078	10.0000	2.60000	121	v	2.79078	8.98870	0.00000
45	v	2.79078	7.13120	0.00000	122	v	2.79078	8.98870	1.80000
46	v	2.79078	10.0000	0.00000	123	v	2.79078	8.18870	1.80000
47	v	2.79078	10.0000	2.60000	124	v	2.79078	8.18870	0.00000
48	v	2.79078	7.13120	2.60000	125	v	2.07376	10.0000	0.44064
49	v	3.03078	5.45314	2.60000	126	v	0.43376	10.0000	0.44064
50	v	3.03078	0.00000	2.60000	127	v	0.43376	10.0000	1.80094
51	v	8.00000	0.00000	2.60000	128	v	2.07376	10.0000	1.80094
52	v	8.00000	5.45314	2.60000	129	v	2.79078	2.25787	0.00000
53	v	3.03078	5.45314	0.00000	130	v	2.79078	2.25787	1.80000
54	v	3.03078	0.00000	0.00000	131	v	2.79078	3.05787	1.80000
55	v	8.00000	0.00000	0.00000	132	v	2.79078	3.05787	0.00000
56	v	8.00000	5.45314	0.00000	133	v	2.24241	0.00000	0.00000
57	v	3.03078	0.00000	0.00000	134	v	0.94241	0.00000	0.00000
58	v	8.00000	0.00000	0.00000	135	v	0.94241	0.00000	2.00000
59	v	8.00000	0.00000	2.60000	136	v	2.24241	0.00000	2.00000
60	v	3.03078	0.00000	2.60000	137	v	0.00000	2.40013	1.80094
61	v	3.03078	5.45314	0.00000	138	v	0.00000	4.30013	1.80094
62	v	3.03078	0.00000	0.00000	139	v	0.00000	4.30013	0.90094
63	v	3.03078	0.00000	2.60000	140	v	0.00000	2.40013	0.90094
64	v	3.03078	5.45314	2.60000	141	v	0.00000	6.54000	0.34000
65	v	8.00000	5.45314	0.00000	142	v	6.24000	5.45314	0.34000
66	v	3.03078	5.45314	0.00000	143	v	3.03078	5.12000	0.34000
67	v	3.03078	5.45314	2.60000	144	v	3.82000	10.0000	0.34000
68	v	8.00000	5.45314	2.60000	145	v	4.00000	0.00000	0.34000
69	v	8.00000	0.00000	0.00000	146	v	0.43000	10.0000	1.95000

70	v	8.00000	5.45314	0.00000	147	v	2.54000	0.00000	1.25000
71	v	8.00000	5.45314	2.60000	148	v	3.03078	5.26000	1.25000
72	v	8.00000	0.00000	2.60000	149	v	0.30000	0.00000	2.30000
73	v	8.00000	5.69314	2.60000	150	v	3.03078	1.90000	2.30000
74	v	8.00000	10.0000	2.60000	151	v	5.10000	5.69314	2.30000
75	v	3.03078	10.0000	2.60000	152	v	2.80000	8.00000	2.30000
76	v	3.03078	5.69314	2.60000	153	v	0.30000	0.00000	1.50000
77	v	8.00000	5.69314	0.00000	154	v	0.30000	0.00000	1.50000

Appendix IV: Detailed building element inventory of case study 1

Table 7-5: Detailed building element inventory of case study 1

ID	DIN 276	Building element	Sur-face [m²]	Volume [m³]	Mass [kg]	Material	Room Ref.	min. Vol.	max. Vol.
2	351	Ceiling	21.55	2.15	1724	Timber	1	0.75	3.23
3	324	Floor	21.55	4.31	3448	Timber	1	1.50	6.46
4	331	Wall	4.65	1.26	1647	Cellular Concrete	1	0.53	1.67
5	331	Wall	16.20	4.03	5251	Cellular Concrete	1	1.86	5.83
6	341	Wall	7.25	1.02	1326	Cellular Concrete	1	1.26	2.61
7	341	Wall	16.47	2.12	2765	Cellular Concrete	1	2.88	5.93
8	351	Ceiling	9.36	0.93	749	Timber	2	0.32	1.40
9	324	Floor	9.36	1.87	1498	Timber	2	0.65	2.80
10	341	Wall	7.25	1.02	1326	Cellular Concrete	2	1.26	2.61
11	331	Wall	7.45	1.93	2521	Cellular Concrete	2	0.85	2.68
12	331	Wall	5.02	1.35	1762	Cellular Concrete	2	0.57	1.80
13	341	Wall	6.01	0.87	1133	Cellular Concrete	2	1.05	2.16
14	351	Ceiling	29.59	2.95	2367	Timber	3	1.03	4.43
15	324	Floor	29.59	5.91	4735	Timber	3	2.07	8.87
16	331	Wall	12.91	3.25	4225	Cellular Concrete	3	1.48	4.65

17	341	Wall	12.73	1.67	2181	Cellular Concrete	3	2.22	4.58
18	331	Wall	11.47	2.90	3776	Cellular Concrete	3	1.32	4.13
19	331	Wall	11.59	2.93	3811	Cellular Concrete	3	1.33	4.17
20	351	Ceiling	23.62	2.36	1890	Timber	4	0.82	3.54
21	324	Floor	23.62	4.72	3780	Timber	4	1.65	7.08
22	331	Wall	1.44	0.49	643	Cellular Concrete	4	0.16	0.51
23	341	Wall	9.75	1.32	1716	Cellular Concrete	4	1.70	3.51
24	331	Wall	12.91	3.25	4225	Cellular Concrete	4	1.48	4.65
25	331	Wall	10.31	2.62	3413	Cellular Concrete	4	1.18	3.71
26	3341	Door frame	0.29	0.09	13.82	Timber	4	0	0.03
26	3341	Door wing	1.15	0.09	55.3	Timber	4	0.01	0.12
27	3341	Door frame	0.29	0.09	6.91	Timber	4	0	0.01
27	3341	Door wing	1.15	0.09	27.65	Timber	4	0.01	0.06
28	3342	Window frame	0.18	0.01	5.63	Timber	4	0	0.02
28	3342	Window wing	0.7	0.03	22.53	Timber	4	0.01	0.07
28	3342	Window glass	0.7	0.01	17.95	Glass	4	0	0.01
29	3341	Door frame	0.29	0.09	13.82	Timber	3	0	0.03
29	3341	Door wing	1.15	0.09	55.3	Timber	3	0.01	0.12
30	3341	Door frame	0.29	0.09	6.91	Timber	3	0	0.01
30	3341	Door wing	1.15	0.09	27.65	Timber	3	0.01	0.06
31	3342	Window frame	0.52	0.02	16.56	Timber	3	0.01	0.05
31	3342	Window wing	2.07	0.08	66.23	Timber	3	0.02	0.21
31	3342	Window glass	2.07	0.02	52.78	Glass	3	0.01	0.04
32	3341	Door frame	0.29	0.09	6.91	Timber	2	0	0.01
32	3341	Door wing	1.15	0.09	27.65	Timber	2	0.01	0.06
33	3342	Window frame	0.45	0.02	14.28	Timber	2	0	0.04
33	3342	Window wing	1.78	0.07	57.11	Timber	2	0.02	0.18
33	3342	Window glass	1.78	0.02	45.51	Glass	2	0.01	0.04
34	3341	Door frame	0.29	0.09	6.91	Timber	1	0	0.01
34	3341	Door wing	1.15	0.09	27.65	Timber	1	0.01	0.06
35	3341	Door frame	0.52	0.16	24.96	Timber	1	0.01	0.05
35	3341	Door wing	2.08	0.16	99.84	Timber	1	0.02	0.21
36	3342	Window frame	0.34	0.01	10.94	Timber	1	0	0.03
36	3342	Window wing	1.37	0.05	43.78	Timber	1	0.01	0.14
36	3342	Window glass	1.37	0.01	34.88	Glass	1	0.01	0.03
37	44411	Wiring, 3-strand	0	0.0001	0.65	Cable	1	0	0.0006
37	44441	Outlet	0	0.0001	0.20	PVC	1	0.0001	0.0001
38	44411	Wiring, 3-strand	0	0.0001	0.64	Cable	3	0	0.0006

38	44441	Outlet	0	0.0001	0.20	PVC	3	0.0001	0.0001
39	44411	Wiring, 3-strand	0	0.0002	0.82	Cable	3	0.0001	0.0004
39	44441	Outlet	0	0.0001	0.20	PVC	3	0.0001	0.0001
40	44411	Wiring, 3-strand	0	0.0001	0.55	Cable	4	0	0.0005
40	44441	Outlet	0	0.0001	0.20	PVC	4	0.0001	0.0001
41	44411	Wiring, 3-strand	0	0	0	Cable	3	0	0
41	44441	Outlet	0	0.0001	0.20	PVC	3	0.0001	0.0001
42	44411	Wiring, 3-strand	0	0.00009	0.34	Cable	2	0	0.0003
42	44441	Outlet	0	0.0001	0.20	PVC	2	0.0001	0.0001
43	44411	Wiring, 3-strand	0	0	0	Cable	1	0	0
43	44441	Outlet	0	0.0001	0.20	PVC	1	0.0001	0.0001
44	44411	Wiring, 3-strand	0	0.0001	0.71	Cable	3	0.00008	0.0003
44	44441	Outlet	0	0.0001	0.20	PVC	3	0.0001	0.0001
45	44411	Wiring, 3-strand	0	0.00003	0.11	Cable	1	0	0.00006
45	44421	DistributionBox	0	0.0001	0.10	PVC	1	0.0001	0.0001
46	44411	Wiring, 3-strand	0	0.0002	0.80	Cable	3	0	0.0004
46	44421	DistributionBox	0	0.0001	0.10	PVC	3	0.0001	0.0001
47	44411	Wiring, 3-strand	0	0.0004	1.67	Cable	4	0	0.0008
47	44421	DistributionBox	0	0.0001	0.10	PVC	4	0.0001	0.0001
48	44411	Wiring, 3-strand	0	0.0004	1.67	Cable	2	0	0.0008
48	44421	DistributionBox	0	0.0001	0.10	PVC	2	0.0001	0.0001
49	44411	Wiring, 3-strand	0	0	0	Cable	2	0	0
49	44421	DistributionBox-Level	0	0.0001	0.10	Aluminum	2	0.0001	0.0001
50	44411	Wiring, 3-strand	0	0	0	Cable	1	0	0
50	44422	DistributionBox-Building	0	0.05	4.00	Aluminum	1	0.05	0.05

Appendix V: Deconstruction activities and their durations [h] in the baseline scenario no. 14 of case study 2

Table 7-6: Deconstruction activities and their durations [h] in the baseline scenario no. 14 of case study 2 (none = all rooms, R1= room 1, etc.)

ID	Deconstruction activity	Modes								
		1	2	3	4	5	6	7	8	9
1	'ID: 1 Start'	0,000	0,000	0,000	0,000	0,000	0,00	0,000	0,000	0,000
2	'ID: 2 Foundations‘	0,178	0,462	0,247	0,213	0,056	0,790	0,085	0,138	0,035
3	'ID: 3 Floor Slab Covering’	0,177	1,109	0,218	0,213	0,809	1,037	0,047	0,075	0,761
4	'ID: 4 Walls'	0,590	2,113	0,704	0,688	1,005	2,848	0,153	0,248	0,931
5	'ID: 5 Ceilings'	0,225	0,564	0,306	0,264	0,054	0,974	0,088	0,142	0,035
6	'ID: 6 Ceiling Covering, R1	0,000	0,157	0,090	0,078	0,097	0,070	0,060	0,097	0,000
7	'ID: 7 Doors'	0,228	0,557	0,322	0,268	0,018	0,972	0,097	0,156	0,000
8	'ID: 8 Windows, R1	0,000	0,092	0,052	0,005	0,006	0,004	0,035	0,056	0,000
9	'ID: 9 TEQ HEAT, R1'	0,000	0,000	0,000	0,000	0,000	0,000	0,016	0,026	0,000
10	'ID: 10 TEQ POWER, R1'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,002	0,000
11	'ID: 11 TEQ POWER, R2'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
12	'ID: 12 TEQ POWER, R3'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
13	'ID: 13 Windows, R4'	0,005	0,045	0,026	0,006	0,000	0,022	0,014	0,023	0,000
14	'ID: 14 TEQ POWER, R4'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
15	'ID: 15 TEQ POWER, R5'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
16	'ID: 16 TEQ POWER, R6'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000
17	'ID: 17 Windows, R7'	0,000	0,046	0,026	0,004	0,005	0,004	0,018	0,029	0,000
18	'ID: 18 TEQ POWER, R7'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
19	'ID: 19 TEQ POWER, R8'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
20	'ID: 20 Windows, R9'	0,000	0,046	0,026	0,004	0,005	0,004	0,018	0,029	0,000
21	'ID: 21 TEQ POWER, R9'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000
22	'ID: 22 TEQ POWER, R10'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
23	'ID: 23 Windows, R11'	0,000	0,046	0,026	0,004	0,005	0,004	0,018	0,029	0,000
24	'ID: 24 TEQ POWER, R11'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
25	'ID: 25 Wall Covering, R12'	0,000	0,043	0,025	0,022	0,027	0,019	0,016	0,027	0,000
26	'ID: 26 Ceiling Covering, R12'	0,000	0,016	0,009	0,008	0,010	0,007	0,006	0,010	0,000
27	'ID: 27 TEQ W+WW, R12'	0,008	0,000	0,000	0,000	0,000	0,000	0,006	0,025	0,000
28	'ID: 28 TEQ HEAT, R12'	0,000	0,000	0,000	0,000	0,000	0,000	0,008	0,013	0,000
29	'ID: 29 TEQ POWER, R12'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000
30	'ID: 30 Windows, Room13'	0,000	0,046	0,026	0,004	0,005	0,004	0,018	0,029	0,000
31	'ID: 31 TEQ POWER, R13'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
32	'ID: 32 TEQ POWER, R14'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
33	'ID: 33 Windows, R15'	0,000	0,046	0,026	0,004	0,005	0,004	0,018	0,029	0,000
34	'ID: 34 TEQ POWER, R15'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000

35	'ID: 35 TEQ POWER, R16'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
36	'ID: 36 Windows, R17'	0,000	0,046	0,026	0,004	0,005	0,004	0,018	0,029	0,000
37	'ID: 37 TEQ POWER, R17'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000
38	'ID: 38 Windows, R18'	0,002	0,000	0,000	0,000	0,000	0,000	0,002	0,003	0,000
39	'ID: 39 TEQ POWER, R18'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
40	'ID: 40 Wall Covering, R19'	0,000	0,043	0,025	0,021	0,026	0,019	0,016	0,026	0,000
41	'ID: 41 Ceiling Covering, R19'	0,000	0,016	0,009	0,008	0,010	0,007	0,006	0,010	0,000
42	'ID: 42 Windows, R19'	0,037	0,073	0,042	0,041	0,000	0,155	0,008	0,012	0,000
43	'ID: 43 TEQ HEAT, R19'	0,000	0,000	0,000	0,000	0,000	0,000	0,008	0,013	0,000
44	'ID: 44 TEQ POWER, R19'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
45	'ID: 45 Windows, Room20'	0,016	0,093	0,054	0,018	0,000	0,068	0,027	0,043	0,000
46	'ID: 46 TEQ POWER, R20'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
47	'ID: 47 Windows, R21'	0,000	0,054	0,031	0,017	0,021	0,015	0,021	0,033	0,000
48	'ID: 48 TEQ POWER, R21'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000
49	'ID: 49 Windows, R22'	0,007	0,055	0,032	0,008	0,000	0,029	0,017	0,028	0,000
50	'ID: 50 TEQ POWER, R22'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
51	'ID: 51 Windows, R23'	0,005	0,024	0,014	0,005	0,000	0,019	0,007	0,011	0,000
52	'ID: 52 TEQ POWER, R23'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
53	'ID: 53 TEQ POWER, R24'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000
54	'ID: 54 TEQ POWER, R25'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
55	'ID: 55 Ceiling Covering, R26'	0,000	0,124	0,071	0,062	0,076	0,055	0,047	0,076	0,000
56	'ID: 56 TEQ HEAT, R26'	0,000	0,000	0,000	0,000	0,000	0,000	0,016	0,026	0,000
57	'ID: 57 TEQ POWER, R26'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
58	'ID: 58 Windows, R27'	0,000	0,020	0,011	0,004	0,004	0,003	0,008	0,012	0,000
59	'ID: 59 TEQ POWER, R27'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
60	'ID: 60 TEQ POWER, R28'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
61	'ID: 61 TEQ POWER, R29'	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,001	0,000
62	'ID: 62 End'	0,000	0,000	0,000	0,000	0,000	0,00	0,000	0,000	0,000

Appendix VI: Deconstruction strategies and robustness criteria of case study 2

Table 7-7: List of deconstruction strategies in case study 2

No	Deconstruction strategy	Opt. in Scen.	C_{max} μ	C_{max} $σ^2$	C_{max} σ	C_{max} μ-σ	C_{max} AR
1	[1;13;51;49;42;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][3;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][4;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][17;33;30;47;23;20;36;8;41;26;55;5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][58;9;28;56;27;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][15;34;44;10;19;54;29;31;48;21;37;45;16;46;52;11;53;59;18;32;39;22;50;61;60;43;57;24;35;7;12;14;38;40;25;6][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	27	1906	499849	707	1199	1355
2	[1;27;13;38;51;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][20;17;33;7;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][45;42;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][23;49;36;58;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;30;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][43;9;28;56;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][12;22;32;21;35;54;46;50;59;48;52;61;19;44;60;11;18;24;14;15;53;10;31;37;16;34;39;29;57;25;55;26;3;5;4;2][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	3	1856	527076	726	1130	0
3	[1;27;38;45;49;42;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][7;5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][23;51;30;8;33;13;58;47;17;36;20;40;6;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][9;43;28;4;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][15;34;46;14;18;60;29;44;56;12;16;48;19;37;50;10;31;53;11;21;61;24;32;35;22;39;57;52;54;59;25;55;26;3][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	16	1856	527076	726	1130	0
4	[1;27;38;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][42;17;30;8;58;25;6;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][23;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][45;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][43;20;51;33;9;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][12;28;32;11;54;56;13;22;24;10;15;18;31;35;50;29;44;46;16;59;34;14;19;49;52;48;60;37;21;36;53;39;47;61;57;55][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	18	1875	514089	717	1158	521

5	[1;27;42;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][36;38;30;23;40;25;55;26;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][33;17;49;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][51;8;58;20;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;28;9;56;45;43;13;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][11;59;61;44;53;57;32;46;54;48;52;60;12;16;22;14;15;18;19;37;50;10;29;31;21;24;39;34;35][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	20	1863	521284	722	1141	175
6	[1;27;43;28;49;51;38;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][45;58;42;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;20;13;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;8;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][17;33;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][23;36;56;7;3;5;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][39;44;59;29;50;53;14;35;57;19;34;60;11;46;61;10;16;18;22;24;54;9;31;52;21;37;48;12;15;32;25;40;55;41;4][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	14	1856	527076	726	1130	0
7	[1;27;45;38;13;28;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;58;42;49;40;25;26;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][33;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][51;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][20;23;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][9;43;56;17;30;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][34;37;44;12;18;52;21;29;31;19;48;53;14;39;46;11;16;54;22;32;50;10;15;35;24;57;61;7;36;59;60;55][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	12	1863	519841	721	1142	186
8	[1;27;49;7;38;13;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][33;23;51;17;47;8;25;26;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][58;45;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][42;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][36;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][20;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][15;53;61;11;54;57;14;44;59;22;37;48;18;21;31;19;28;52;24;9;32;16;46;50;10;56;29;43;35;60;39;12;34;41;55][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	11	1872	515524	718	1154	433
9	[1;27;51;38;45;9;43;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][36;23;58;25;6;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][49;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][42;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;17;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;33;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;20;13;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][14;24;48;18;34;61;10;11;50;31;44;60;15;32;46;29;54;57;12;16;53;22;28;56;39;19;59;37;35;21;52;55][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	13	1871	515524	718	1153	410

10	[1;27;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][51;45;23;25;40;55;26;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;58;42;17;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][49;36;13;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][43;28;56;20;9;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][12;32;57;34;48;53;8;11;30;16;37;38;15;29;50;10;19;54;33;44;61;18;35;52;39;46;60;14;24;22;21;59;31;41][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	26	1859	524176	724	1135	75
11	[1;27;9;28;43;51;13;49;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][20;40;25;6;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][33;17;42;45;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;36;23;58;55;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][56;38;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][16;19;61;22;48;54;14;50;57;12;37;46;15;21;53;35;59;60;10;39;52;11;31;34;18;24;44;29;32][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	10	1873	515524	718	1155	449
12	[1;38;27;45;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][17;51;42;47;20;23;25;6;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][36;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][13;33;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][49;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;56;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][15;32;37;18;39;52;24;28;44;43;46;50;34;60;61;58;12;14;29;59;19;54;53;57;31;21;11;9;16;35;48;10;22;41;55][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	17	1864	519841	721	1143	228
13	[1;38;51;27;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][33;17;58;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;13;30;20;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][45;8;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][25;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][56;42;9;43;28;23;36;4;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][10;29;60;16;21;50;15;19;31;22;34;46;35;39;59;11;53;54;37;49;57;44;48;61;12;14;52;18;24;32;7;40;55;6;26;41;3;5;2][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	23	1856	527076	726	1130	0
14	[1;42;13;4;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][51;49;3;5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;58;8;17;23;20;55;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][45;47;36;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][15;27;34;33;37;57;18;31;59;12;14;39;24;43;7;29;60;61;21;35;9;22;46;16;11;44;53;52;10;38;56;28;32;48;54;50;19;40;25;6;41][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	25	1958	491401	701	1257	2760

15	[1;42;49;38;43;9;56;45;51;28;13;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][17;36;58;33;47;30;20;23;6;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][27;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][14;21;52;19;57;60;15;16;61;10;18;35;37;50;59;29;32;44;11;34;53;8;12;48;24;31;54;22;39;46;25;40;55;26][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	1	1880	514089	717	1163	660
16	[1;42;49;45;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][3;5;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][4;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;51;33;17;13;36;47;20;23;58;25;40;6;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][43;38;56;9;27;28;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;14;50;16;32;53;31;46;57;12;39;44;29;34;52;21;22;24;15;18;54;48;59;61;10;35;60;11;19;37;7;55;41][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	19	1902	501264	708	1194	1250
17	[1;42;51;13;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][49;5;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][4;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;8;33;36;30;58;20;23;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][43;28;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][18;32;45;50;54;61;22;24;35;19;29;39;17;52;53;44;48;60;7;59;11;21;10;12;14;56;27;9;37;46;31;38;57;16;34;15;25;40;26;6;55;3][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	8	2016	549081	741	1275	4316
18	[1;42;56;49;27;51;9;38;43;28;45;13;3;4;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][7;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][20;23;30;33;8;17;58;47;36;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][11;12;15;18;22;60;19;34;37;48;52;59;14;29;44;16;31;46;10;39;57;21;24;50;32;35;53;54;61;25;55;6;26;41;5;2][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	5	1856	527076	726	1130	0
19	[1;42;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][13;30;45;20;36;38;7;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][33;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;17;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][49;23;58;51;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;56;9;28;27;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][21;24;48;22;46;54;12;52;60;10;14;44;15;29;34;19;32;53;11;16;43;31;39;59;18;35;50;37;57;61;25;55;26;3;5;4;2][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	15	1856	527076	726	1130	0

20	[1;43;38;56;28;49;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][42;45;25;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][20;51;30;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][13;23;58;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][36;33;47;8;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][9;17;27;7;40;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][12;15;59;11;19;37;24;29;31;18;39;61;22;35;54;44;46;48;10;34;53;16;32;60;14;21;57;50;52;55;6;26;3;4][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	9	1856	527076	726	1130	0
21	[1;45;13;49;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][7;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][3;5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][20;51;36;30;33;47;17;23;58;42;6;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][43;28;27;9;56;38;4;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;18;31;22;32;50;21;34;60;10;24;37;14;35;59;12;44;61;19;29;39;16;46;54;11;15;57;48;52;53;25;40;55;26;41][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	2	1856	527076	726	1130	0
22	[1;45;13;4;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][51;49;3;5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][17;42;58;23;30;20;55;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][56;47;9;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][21;37;44;19;36;52;24;28;50;29;38;57;54;60;7;53;39;61;46;27;59;43;34;33;31;8;35;48;32;10;22;14;16;18;11;12;15;40;25;26;6;41][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	6	2072	657721	811	1261	5844
23	[1;45;51;42;7;49;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][3;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][17;33;47;20;30;8;13;36;58;40;25;6;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][9;43;56;27;38;28;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][11;12;31;16;39;50;35;48;54;22;24;46;23;37;53;14;19;60;15;18;59;21;57;61;10;29;44;32;34;52;41;55;26;4][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	4	1856	527076	726	1130	0
24	[1;45;51;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][42;3;4;2;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][36;47;58;23;33;30;13;20;41;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][56;9;27;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][29;32;48;8;31;61;12;17;37;22;50;53;16;54;57;21;24;52;39;7;60;14;59;38;18;35;10;34;46;43;49;28;44;11;19;15;25;40;55;6][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	21	1904	502681	709	1195	1296

25	[1;49;13;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][7;3;5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][4;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][17;33;42;36;51;20;30;45;23;58;47;25;6;26;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][28;56;9;27;43;38;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][18;44;57;8;14;54;21;29;50;15;31;48;11;35;60;24;37;61;19;53;59;34;46;52;10;16;22;12;32;39;40;55;41;2][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	7	1885	505521	711	1174	792
26	[1;56;27;51;45;49;38;28;43;7;3;5;4;2;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;23;13;17;25;6;26;55;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][58;30;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][33;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][36;20;9;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][34;39;48;18;44;61;11;12;14;19;50;57;35;42;54;21;29;52;15;37;53;16;22;31;24;32;59;46;10;60;41][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	22	1873	515524	718	1155	452
27	[1;9;62;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][49;33;20;17;58;38;13;25;41;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][23;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][42;40;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][47;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][30;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][51;43;27;36;56;28;45;3;5;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0][8;29;31;35;37;59;24;34;39;46;50;53;19;44;57;11;15;60;12;22;61;10;18;32;14;16;21;48;52;54;7;55;6;26;4;2][0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0]	24	1856	527076	726	1130	0

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In this research, a project planning and decision support model is developed and applied to identify and reduce risk and uncertainty in deconstruction project planning. The developed model allows calculating building inventories based on sensor information and construction standards as well as computing robust project plans for different project framework conditions. For this purpose, a proactive scenario construction is developed and time-optimal project plans are calculated with multiple modes, constrained resources and locations (MRCPSP) for each scenario. Locations are explicitly modeled which helps to avoid working team jamming and to improve onsite logistics of machinery, material and building elements. Then, the most optimality-robust deconstruction strategy is identifi ed and recommended to decision makers according to their risk attitude. Also, a reactive and fl exible model element based on local search or rescheduling is proposed in the case of schedule infeasibility during project execution. The applicability of the developed model is shown in two case studies comprising both a residential and a non-residential building.

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