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Robust multi-mode resource constrained project scheduling of building deconstruction under uncertainty

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1 Introduction

Buildings are characterized by their immobility, heterogeneity and uniqueness. Due to their long lifecycles, buildings undergo several decades and are refurbished, retrofitted, remediated or modernized by generations of users, residents and proprietaries to adapt the building to changing users' and environmental requirements. During their lifecycles, different building elements and products are installed, removed or changed due to building modification. Often, these modifications of the building structure, equipment and fittings as well as the deterioration and contamination of buildings are not documented. In addition, some buildings cannot economically be adapted to changing requirements. The buildings in question undergo deconstruction (and replacement) processes, often in spatially limited sites of dense urban areas and with limited resources available. The objective of the responsible stakeholders of the deconstruction is either makespan minimization or cost minimization or both depending on the type of building, the urgency or the preference of the responsible parties.

In building deconstruction, different scarce renewable resources (machines, staff) can be applied to perform so called jobs like separation, deconstruction, crushing, sorting and loading activities that might 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. Job shop scheduling on m machines where each job has its own predetermined route [1] 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 [2]. 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. Thus, here we consider a multi-mode project scheduling problem ($MPS \mid prec \mid C_{max}$) under resource constraints (MRCPSP) and with zero-lag finish-start precedence relations (notation according to [3,4]). Single-mode and multi-mode project scheduling problems are a generalization of job shop scheduling problems [2,3,5,6]. This problem class is NP complete [2].

The consideration of uncertainty is crucial in deconstruction projects to reduce disruptions and vulnerability of the project. Uncertainties in project scheduling might arise from work content, resource availabilities, precedence constraints in the project network etc. [7]. In deconstruction projects, main sources of uncertainty are processing times of activities and the existence of activities which depend on the building configuration (set of building elements and their specific properties such as different secondary raw materials or hazardous materials) and onsite resource and location availability and capacity (such as staff, hydraulic excavators, site equipment, containers etc.). Since uncertainty is mostly caused by building inherent elements, in a first step our approach restricts to the creation of a robust schedule which is the proactive consideration of potential disturbances resulting from building elements to avoid multiple changes in schedules. Other uncertainties onsite (resource availability) might be considered in a second step regarding

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project execution e.g. via reactive scheduling and repairing methods in multi-period scheduling that are not considered in this contribution.

First, our contribution will give a short literature overview about existing scheduling models under the consideration of uncertainty. Subsequently, we will give a brief summary of our scheduling model for building deconstruction under uncertainty and first results. Our contribution is concluded by a short summary and outlook.

2 Literature review

Literature about project scheduling under uncertainty is extensive and several publications are dedicated to predictive-reactive, proactive (robust), fuzzy and stochastic scheduling [8]. Research focuses on the development of proactive schedules and reactive (reparation) strategies in the case of schedule infeasibility during project execution and some work has already been done in the field of proactive and reactive project scheduling for the single-mode RCPSP [9]. Main approaches focus on the consideration of duration variability and related buffer insertion procedures [10,11] or resource unavailability [12]. However, literature on proactive-reactive scheduling in multi-mode RCPSP (MRCPSP) is still quite rare [9]. Fuzzy scheduling is based on expert estimations of activity durations whereas stochastic scheduling is based on known distributions of activity durations. Scenario-based robust scheduling approaches are based on discrete robust optimization (e.g. [13]) and are considered in recent literature for RCPSP where uncertainty is modeled via scenarios using discrete or discretized probabilities [14,15].

In deconstruction projects, activity-based and location-based scheduling can be differentiated. Activity-based scheduling models consider activities explicitly, location-based scheduling describe activities only implicitly by their occupation of locations during activity completion. Activity-based problems with limited renewable (constrained over time periods and available after activity is terminated) and non-renewable (budgeted over the whole project) resources are formulated as RCPSP where scheduling and capacity planning is performed simultaneously [1,3,8,16]. Location-based approaches are often applied in construction projects [17,18] and thus seem promising for deconstruction application, too. Here, we consider a joint activity-based approach where locations are considered as resources that are required for activity performance.

Although robust RCPSP approaches and their problem variants [7,8,19,14,20] are numerous, applied works in deconstruction are rare [2,21–24]. Scheduling applications in deconstruction projects are mainly limited to deterministic approaches [2,22,23,25,26] yet although uncertainties are indispensable when it comes to deconstruction scheduling of decades old and often undocumented buildings at the end of their life cycle. Schultmann (2003) [22] 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). However, this approach does not cover all uncertainties decision makers are confronted with such as fuzzy due dates, fuzzy capacity constraints, uncertain composition of the components or fuzzy precedence relations [22]. 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.

3 Approach

In our approach, a MRCPSP is formulated and solved (B) for several potential scenarios of building configurations (A) and recommendations for decision making in deconstruction projects are given (C) (see Figure 1). Thus, our approach combines a scenario simulation, with robust optimization (scheduling). Due to the buildings' uniqueness the assignment of probabilities of occurrences, e.g. of activity durations or building element existence, is difficult. However, the creation of possible scenarios (building configurations) and related activity durations is possible. Thus, our approach is based on a scenario construction and expert estimates on optimistic, expected and pessimistic activity durations that can be represented by fuzzy sets. A stochastic approach is theoretically possible, but assumptions on parameters of the related beta distribution can only be estimated.

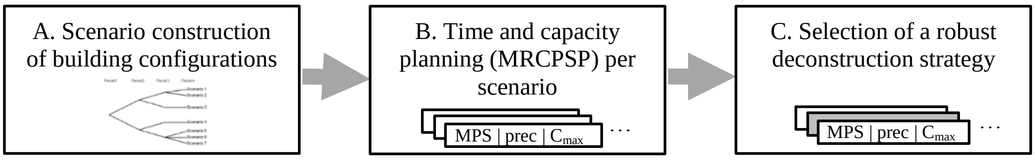

Figure 1: Model overview

3.1 Scenario construction of building configurations

In building deconstruction, several epistemic uncertainties are prevalent (aleatoric uncertainties are not considered in this work since they are hardly quantifiable). Relevant project-related scenario attributes such as the characteristics of building elements, the material of the elements and varying resource capacities contain epistemic uncertainties. Activity-related scenario attributes such as the activity durations also contain epistemic uncertainties which can be e.g. represented by a minimum, expected and maximum duration per activity and per building element unit.

Different scenarios are created via an initial building configuration of an examined building that is varied with other possible discrete project-related and activity-related scenario attributes as described above. In the presented case, each building element is assigned to a single ‘deconstruction activity’ and consequently, ‘building element existence’ and ‘element material’ are not only scenario attributes but also activity-related attributes. Thus, in this case a scenario consists of different occurring parameter values of the mentioned activity-related attributes based on the information just before project start. E.g. a building with reinforced concrete slabs versus timber slabs leads to different activities (existence) and resource demands (durations, modes) to be scheduled. If sample pre-testing revealed specific materials, varying material combinations for the respective building element are excluded from scenario construction.

Complete enumeration theoretically leads to more than $4*10^{12}$ scenarios with 10 different building element types that are permuted with 22 potential element materials (on average 4.7) per building element. We tested the approach so far with 10 to 100 scenarios.

For each scenario, project activities are derived from the respective enumerated building configuration with their belonging activity durations, precedence constraints and renewable resource demands (e.g. machine, staff). Depending on the parameter value ‘element material’ per activity, the expected activity duration is calculated via duration per element unit and per material and the related mode selection is adapted according to technical feasibility. For simplicity, project-related uncertainties such as uncertain resource availabilities are neglected in this model, yet.

3.2 Time and capacity planning (MRCPSP) per scenario

In deconstruction projects, activity j is planned with expected durations $E(d_{jm_j})$ of the respective scenario on limited resources q_j and is subject to acyclic precedence constraints. Deconstruction activities are performed with different resources such as hydraulic excavators, hand-held pneumatic drills, chisels, crane and varying number of skilled staff and associated cost, so-called modes m. Thus, we formulate a classical MRCPSP with activity zero-lag finish-start precedences with the objective of minimizing project makespan. For each scenario, the optimal activity modes and the optimal schedule (start times t and resource usage of each activity) are determined in pre-calculated time windows between earliest finish (EF) and latest finish (LF). For reasons of simplicity and due to the application case, the model restricts to modeling of renewable (r) resources q_{jmr} that can be used in different modes m and equally qualified staff is assumed. A further technical constraint is the restricted selection of activity modes that depend on the prevalent building ‘element material’ that has to be deconstructed. Furthermore, on limited job-sites the definition of location-based activities is helpful to schedule working teams and their resources in different parts the site to avoid obstructing accumulations of resources or material. In a consequence and due to safety reasons, location $l \in L$ is formulated as a specific renewable resource where every activity is at least occupying a location at a time ($q_{jm} \geq 1, \forall\, l \in L$) and in every location only one activity can take place simultaneously ($Q_{lt} = 1\ \forall\, l \in L$):

$$\min\ C_{\max} = \sum_{m=1}^{M_j} \sum_{t=EF_J}^{LF_J} t * x_{Jmt}$$

Subject to:

$$\sum_{m=1}^{M_j} \sum_{t=EF_j}^{LF_j} x_{jmt} = 1, \qquad for\ \ j = 1, \dots, J$$

Time and mode selection constraint

$$\sum_{m=1}^{M_i} \sum_{t=EF_i}^{LF_i} t * x_{im_it} \leq \sum_{m=1}^{M_j} \sum_{t=EF_j}^{LF_j} \left(t - E(d_{jm_j})\right) * x_{jm_jt}, \qquad for\ j = 2, \dots, J;\ i \in P_j;\ m_i \in M_i;\ m_j \in M_j$$

Precedence constraint relations

$$\sum_{j=1}^{J} \sum_{m=1}^{M_j} q_{jmr} \sum_{\tau=t}^{t+d_{jm}-1} x_{jm\tau} \leq Q_{rt} \qquad for\ r \in \{R, L\}, t = 1, \dots, T, q_{jm} \geq 1, Q_{lt} = 1$$

$\forall\, l \in L$, Renewable resource constraint Q_r

$$x_{jmt} \in \{0,1\} \qquad j = 1, \dots, J;\ m_j = 1, \dots M_j$$

, Boolean decision variable deciding on activity j starting at time t in mode m.

The model is implemented as a binary, linear integer problem (BILP) in MATLAB R2015b. The commercial CPLEX solver from IBM ILOG Optimization Studio 12.5.1 is used to solve the problem.

Usual problem sizes in deconstruction start at about 100 activities on 10-15 modes and 30-40 renewable resources. As this is a computably challenging problem and is considerably increased in large deconstruction projects by location resources, we performed first tests with problem instances with 17 real activities, 9 modes, 11 resources and 4 locations that showed promising results. On average, this includes 4.2 potential modes per activity, 2.7 different resources per mode, a resource factor RF=0.24 and a resource strength RS=0 (without locations)[1]. The latter indicates resource scarcity, so that some activities have to be scheduled consecutively [4].

3.3 Selection of a robust, proactive deconstruction strategy

Quality robustness aims at the minimization of the deviation from the best-case scenario objective value (here: makespan), while solution robustness covers the minimization of schedule deviation between scenarios [8,27] to increase preparedness for the worst-case. In deconstruction projects, the focus mostly lies on the compliance with time constraints regarding the project deadline [2] due to tight time schedules of owners and general contractors that will reuse the parcel of land or remaining building parts after the deconstruction is completed. However, changes in schedule are associated with additional setup time and cost to organize necessary resources. Thus, on the one hand quality robustness with a reasonably good objective value under any likely scenario [14] seems appropriate to plan deconstruction projects. On the other hand, a solution-robust (stable) schedule is preferable from a time-based and also from an organizational point of view. Our approach aims at proactively finding a total solution-robust schedule x where all absolute regrets (earliness and tardiness) $AR_k(x) = 0$ for all scenarios $k = 1, \dots, K$ and at the same time finding a solution that comprises the 'most' quality-robust schedule.

In this step, the generated optimum schedules are transformed into deconstruction strategies (sequence of activities and resources/locations used). Then, the deconstruction strategies are

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[1] $RF = \frac{1}{n|R|} \sum_{j=1}^{J} \sum_{r \in R} \delta(q_{jr}), \forall r \in \{R\}$, with $\delta(q_{jr}) = \begin{Bmatrix} 1, for\ q_{jr} > 0 \\ 0, for\ q_{jr} = 0 \end{Bmatrix}$ and $RS = \frac{Q_{rt} - Q_r^{min}}{Q_r^{max} - Q_r^{min}} = 0,\ \forall r \in \{R\}$, where Q_r^{min} and Q_r^{max} are lower and upper bounds of resource capacities. See [4] for further information on definitions of control parameters RF and RS.

applied on all scenarios and the respective project makespan is calculated. The deconstruction strategies of all scenarios are aggregated, assessed and compared with each other via several robustness criteria. Applied robustness criteria are the mean, the variance and the standard deviation of project makespan, as well as Laplace, maxi-min, maxi-max, Hurwicz and Savage-Niehans (regret) criteria. Other possible criteria can be found e.g. in [7]. Results include rankings of alternative deconstruction strategies with respect to deconstruction strategy frequency and mean objective value, mean and standard deviation of objective value and mean and variance of objective value. According to the decision makers' risk preferences, recommendations for the adequate project strategy are given.

The presented approach is based on previous works of MRCP scheduling 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 the combination of the two robustness criteria solution robustness and quality robustness. A proactive approach is more practical for the given application case, as the MRCPSP consists of many activities, modes and resources whose status has to be updated manually when the schedule becomes infeasible. A reactive or dynamic scheduling might become interesting, if auditing and controlling of project status is automated or supported via optical sensors.

4 Conclusion

In the field of building deconstruction the consideration of uncertainties is crucial for project planning, scheduling and management. However, our literature review shows that in this application case most approaches insufficiently apply project scheduling methods under resource constraints and uncertainty. 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.

Further work might be concentrated on the extension of the approach with respect to reactive or dynamic scheduling (e.g. schedule repair or rolling horizon). Also, the examination of non-renewable resource constraints such as project budget might be included and the assumption that each building element is assigned to several activities might be included in an extended case study. Scheduling of multi-projects, multi-skills and dynamic scheduling aspects with unexpected events might be considered, too.

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