A material flow-based optimisation tool for nuclear decommissioning planning

Marco Gehring, Rebekka Volk | Institute for Industrial Production, Karlsruhe Institute of Technology (KIT)

Nuclear Decommissioning & Waste Management Summit 2022, London

Institute presentation

Karlsruhe Institute of Technology

Institute for Industrial Production (IIP)

Chair of Business Administration, Production and Operations Management (Prof. Frank Schultmann)

- Techno-economic analyses of industrial value chains/networks
- Risk management
- Circular Economy / Industrial Ecology, Resource efficiency
- Integrated environmental protection measures
- **Production and project planning**
- Supply Chain Management
- Biomass usage / Bioeconomy

Interdisciplinary Research groups

- Risk management
- **Project and resource management in the built environment**
- Sustainable value chains

Chair of Energy Economics (Prof. Wolf Fichtner)

Techno-economic analyses along the whole energetic value chain

French-German Institute for Environmental Research (DFIU)

Development of joint solutions for French-German research problems in the environmental areas of air, water, land, waste and energy

http://www.dfiu.kit.edu/

http://www.iip.kit.edu/

7 Research groups

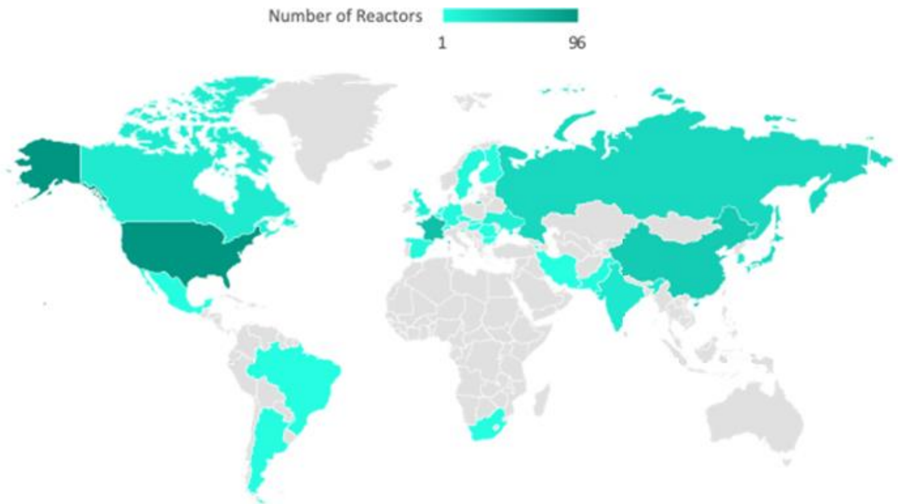
50-60 staff / doctoral candidates (third-party funded)

Agenda

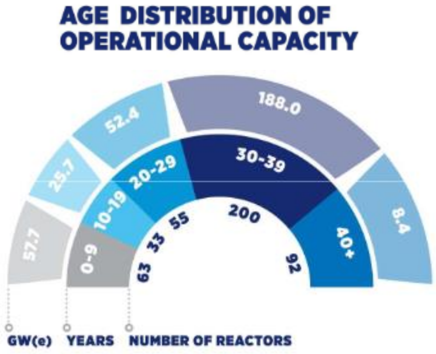
- Motivation
- Project planning
- Material flow planning
- Software OPTIRA
- Conclusions and outlook

Motivation

Aging nuclear power generation reactors induce a massive change in the energy sector worldwide



Total number of operating reactors: **444**
Share of worldwide energy supply: **11%**
Average age of operating reactors: **30 years**



Sources: DAtF (2017), IAEA PRIS (Status: November 2019), Nuclear Power Status 2019, https://pris.iaea.org/pris/PRIS_poster_2019.pdf

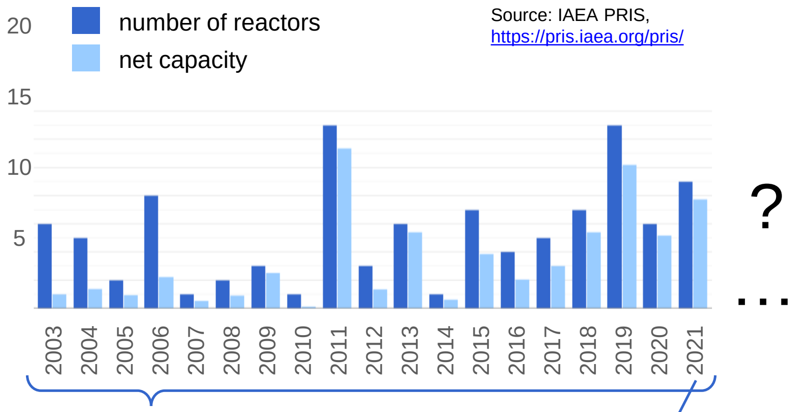
Aging reactors are raising questions about scheduling their retrofitting, replacement or decommissioning

Motivation

The Fukushima Shock – a trend of permanent shutdowns?

Karlsruhe Institute of Technology

Shutdown reactors per year



Ø Ca. 5 per year

BROKDORF	(1410 MW(e), PWR, GERMANY) on 31 December
DUNGENESS B-1	(545 MW(e), GCR, UK) on 7 June
DUNGENESS B-2	(545 MW(e), GCR, UK) on 7 June
GROHNDE	(1360 MW(e), PWR, GERMANY) on 31 December
GUNDREMMINGEN-C	(1288 MW(e), BWR, GERMANY) on 31 December
HUNTERSTON B-1	(490 MW(e), GCR, UK) on 26 November
INDIAN POINT-3	(1030 MW(e), PWR, USA) on 28 April
KANUPP-1	(90 MW(e), PHWR, PAKISTAN) on 1 August
KUOSHENG-1	(985 MW(e), BWR, TAIWAN,CHINA) on 28 December

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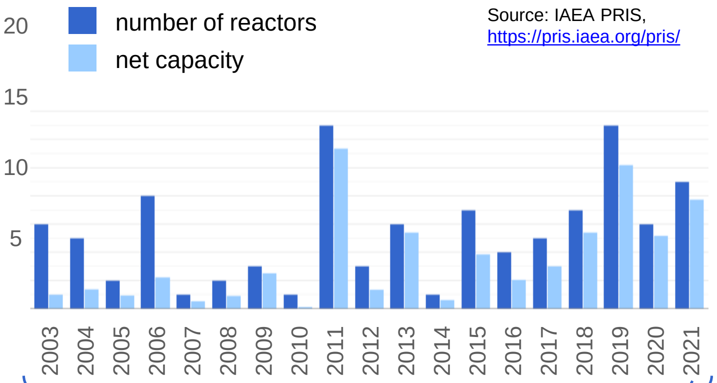
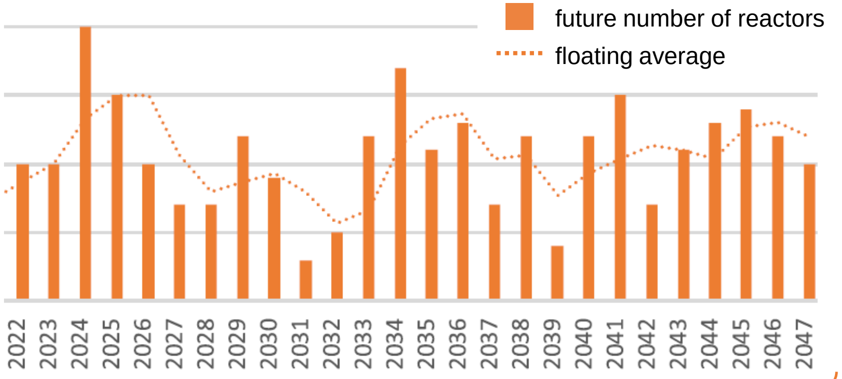


Source: IAEA PRIS, https://pris.iaea.org/pris/



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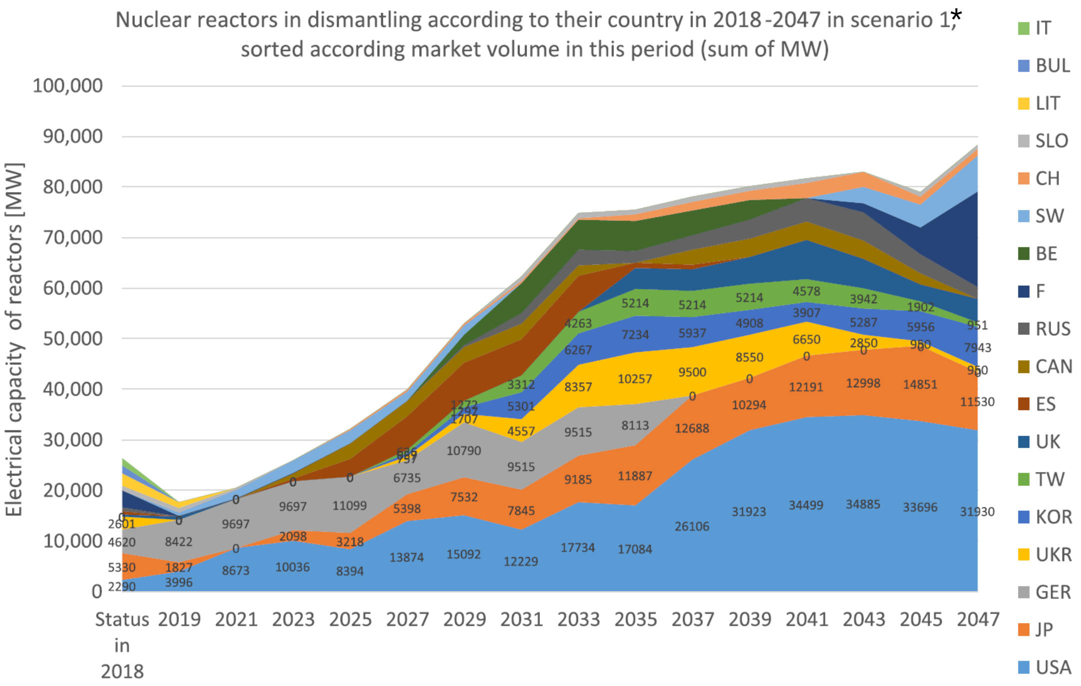
Ø Ca. 10 per year

Source: Volk et al. 2019: https://doi.org/10.1016/j.enpol.2018.08.014

Average annual shutdowns will double in this decade and stay on this level until 2047

Motivation

Increased nuclear dismantling per country



Increasing markets in the **USA, Japan and Spain** later followed by **Ukraine, Korea, Taiwan, UK and Belgium**

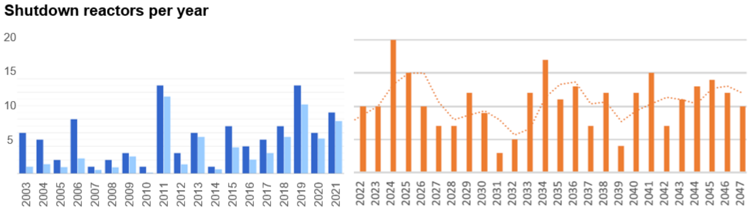
*: Scenario 1 is calculated with expected shutdown dates on reactor-level, a moderate country-specific post-operational phase duration (default: 5.5 years) and a moderate country-specific dismantling duration (default: 10 years).

Source: Volk et al. 2019: https://doi.org/10.1016/j.enpol.2018.08.014

Motivation

Nuclear decommissioning projects …

- … are large-scale projects with long durations, high complexity, and delayed schedules.
- … are costly and exceed foreseen budgets.
- … release large amounts of material (high-, intermediate- and low-level radioactive waste and non-radioactive waste) that require further treatment and conditioning.
- … are facing resource and storage restrictions and ageing staff.
- … will increase.



Research need for **optimal scheduling and cost minimisation** of
nuclear decommissioning projects **under resource and material flow constraints**

NukPlaRStoR:

Development of a user-friendly cost-optimising planning tool for nuclear dismantling projects taking into account material flows for resource planning

SPONSORED BY THE Federal Ministry of Education and Research

Duration: 01/06/2019 – 31/12/2022

Funding code: 15S9414A

Partners: KIT Karlsruhe Institute of Technology, RODIAS, VND Member of Dornier Group

Source: Forschungszentrum Jülich GmbH

Source: EWN Energiewerke Nord GmbH

- Integrated consideration of decommissioning and material flow planning
- Development of a user interface and interfaces to project management software
- Development of logistical planning methods

Further information: https://www.iip.kit.edu/english/1064_4605.php

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Project planning

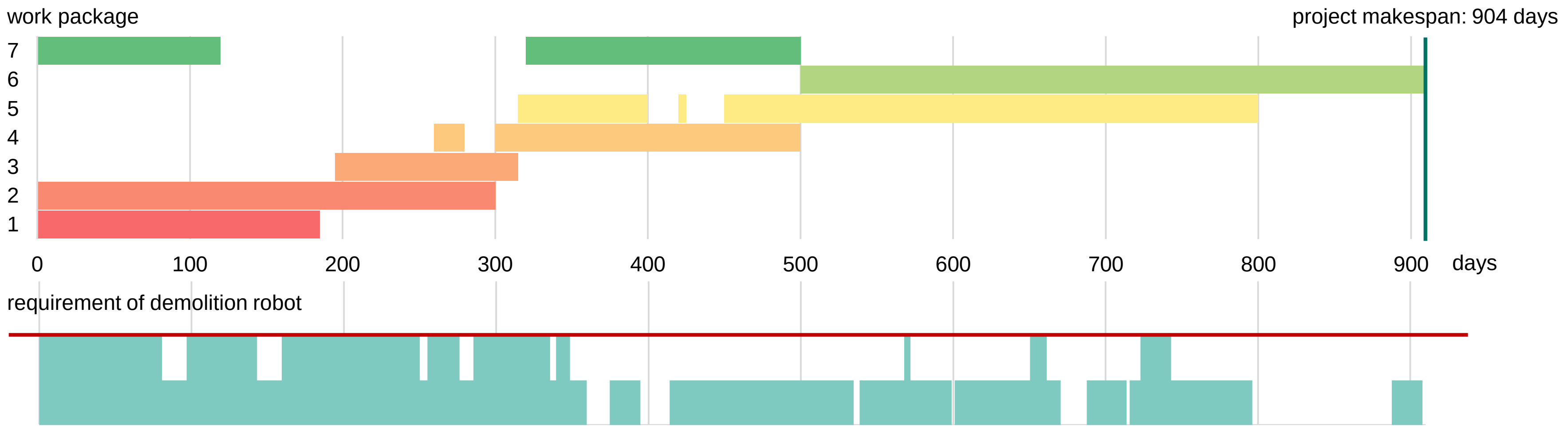
Problem setting (1/2)

Decommissioning of engine house installations of a nuclear power plant in Germany:

7	work packages	e. g. dismantling of turbines
260	activities	e. g. segmentation of pipings, installation of ventilation, dismantling of scaffolding
21	constrained resources	e. g. employees, buzz saw, demolition robot
308	precedence relations	e. g. removal of closure head before removal of installations
2510 days	accumulated duration	

Problem setting (2/2)

Critical-path-based scheduling of activities subject to resource constraints:



Which are the optimal start and end times of activities so that the **project makespan is minimised** and **resource constraints** are satisfied?

Methodological background

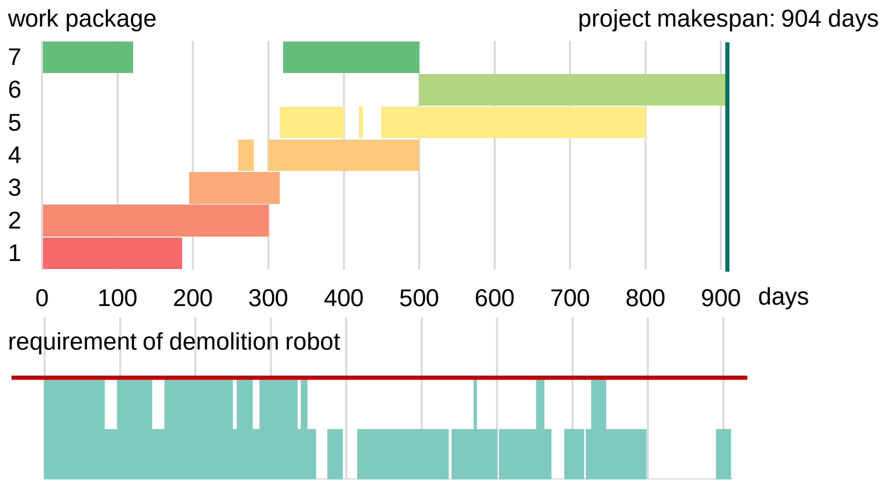
- Mathematical problem:
  - “Resource-constrained project scheduling problem”
  - extensively studied for more than four decades
- Complexity:
  - NP-hard problem: supposedly, there does not exist an efficient algorithm which can solve the problem to optimality for each problem instance
- Solutions:
  - even some problems with 30 activities cannot be solved to optimality where others can be solved within milliseconds (Coelho & Vanhoucke, 2020)
  - there exist algorithms which can compute “very good” solutions for the majority of problem instances

Coelho, J., & Vanhoucke, M. (2020). Going to the core of hard resource-constrained project scheduling instances. *Computers & Operations Research*, *121*.

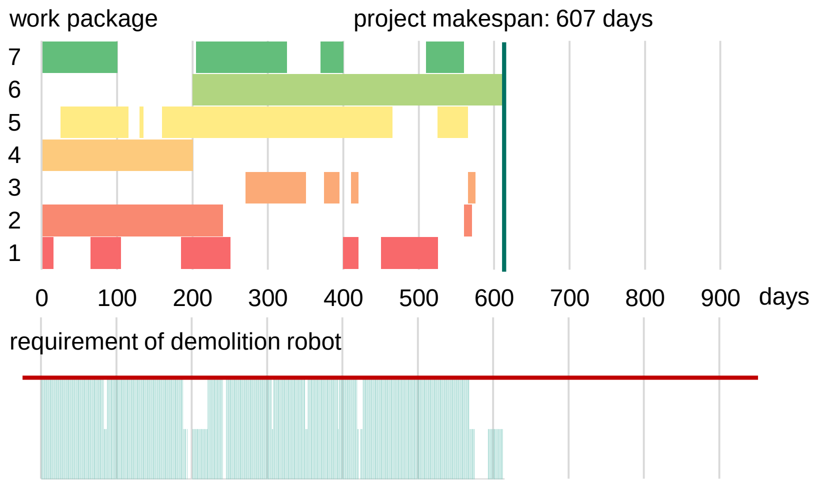
Project planning

Optimisation results

Critical-path-based scheduling:



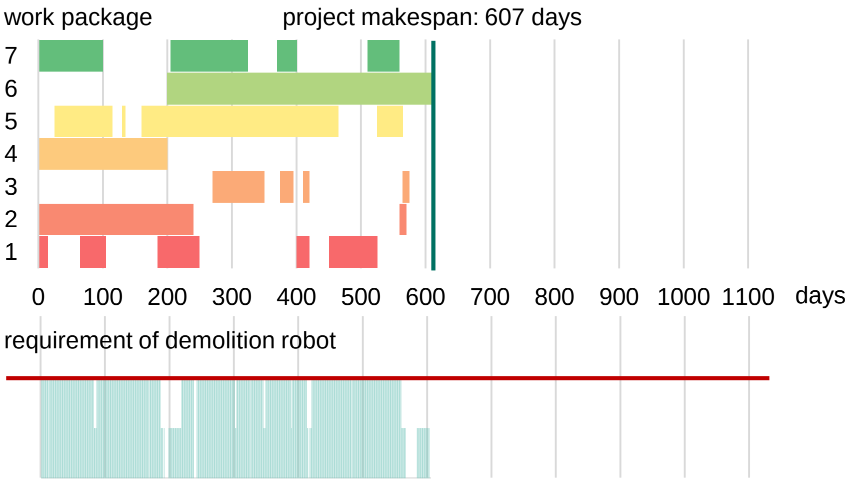
Makespan-optimised scheduling:



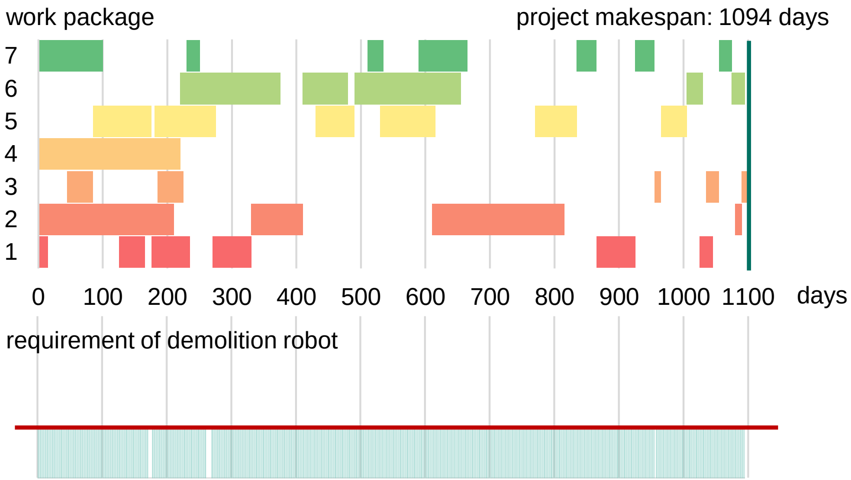
Reduction of project makespan by 296 days (32.8 %)

Scenario analysis

Baseline scenario with two demolition robots:



Scenario with one demolition robot:



Increase of project makespan by 487 days (80.2 %)

Another case study with real-world data

Nuclear decommissioning project in Germany:

7,163	activities
50	constrained resources
8,345	precedence relations

Project makespan **before** optimisation:

Another case study with real-world data

Nuclear decommissioning project in Germany:

7,163	activities
50	constrained resources
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Project makespan **after** optimisation:

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Material flow planning

Problem setting (1/4)

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308	precedence relations	e. g. removal of closure head before removal of installations
2510 days	accumulated duration	
6043 Mg	released materials	e. g. 120 Mg after segmentation of pipings
8	processing steps	e. g. decontamination, conditioning, handing over
5	buffer storages with constrained capacity	

Problem setting (1/4)

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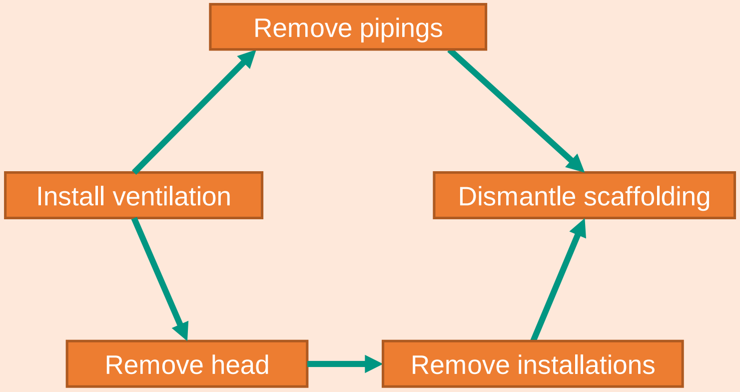
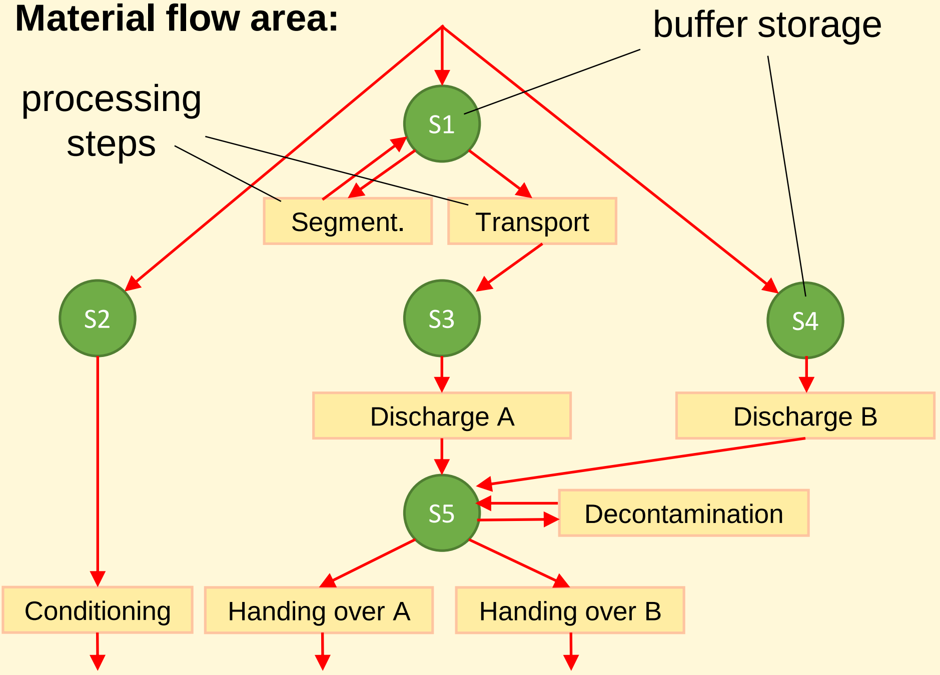
Problem setting (2/4)

Dismantling area:



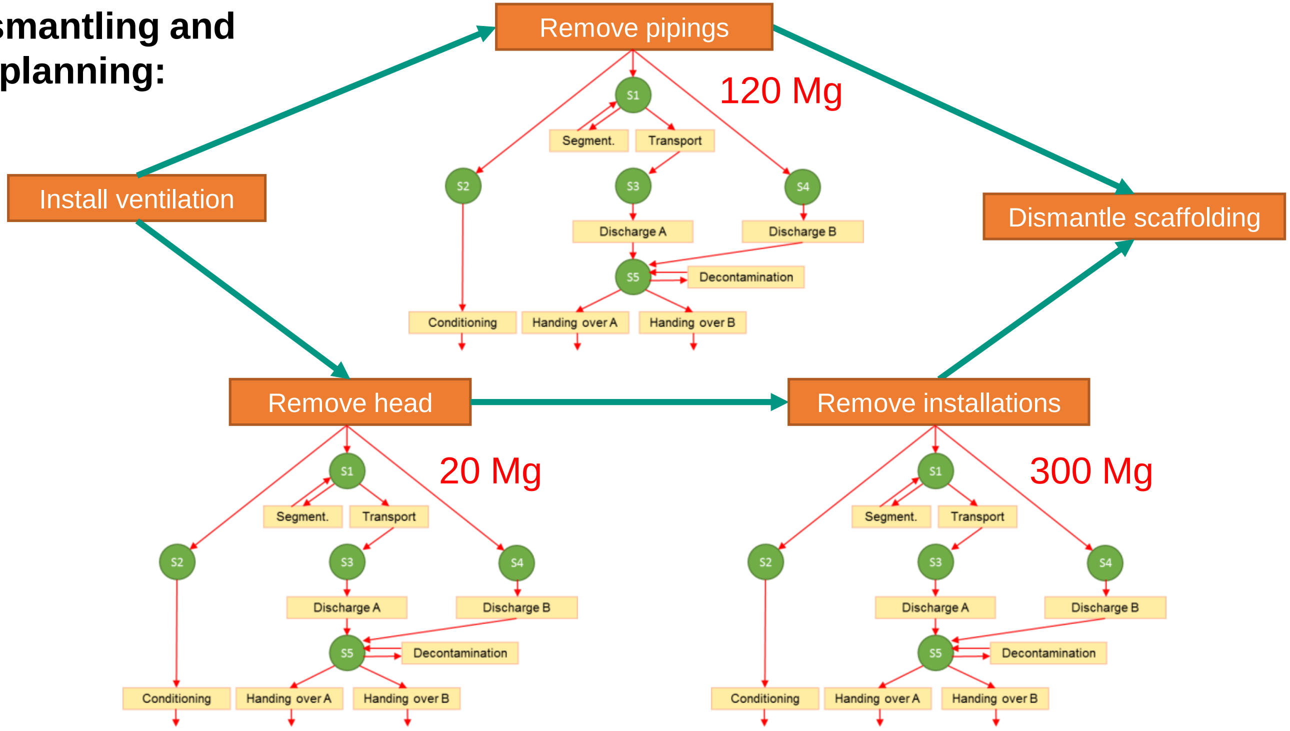
[and others]

Material flow area:



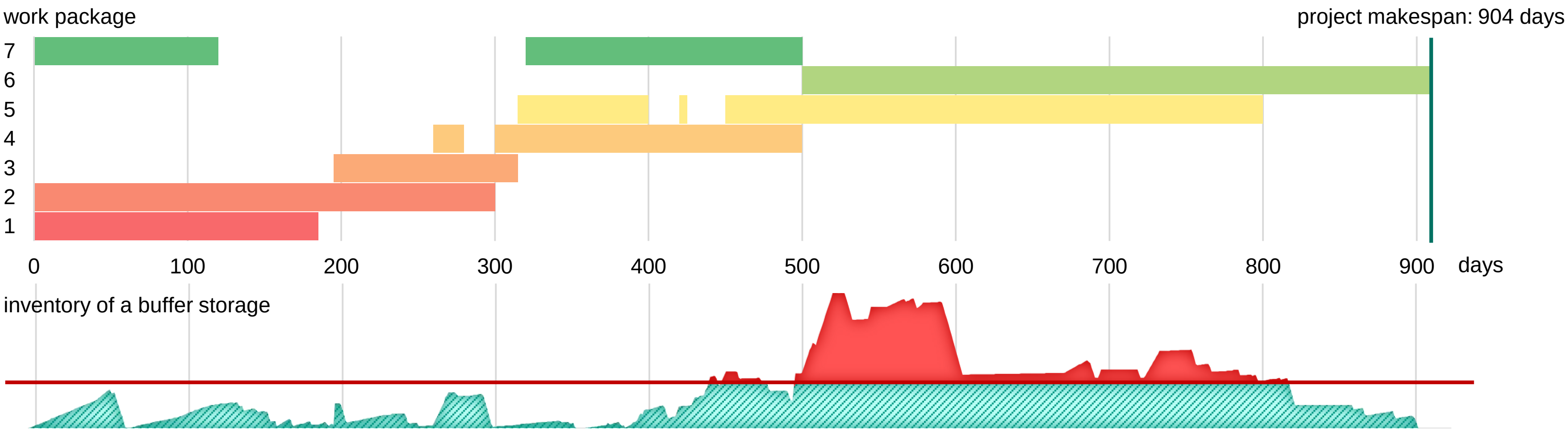
Problem setting (3/4)

Integrated dismantling and material flow planning:



Problem setting (4/4)

Critical-path-based scheduling of activities subject to resource constraints:

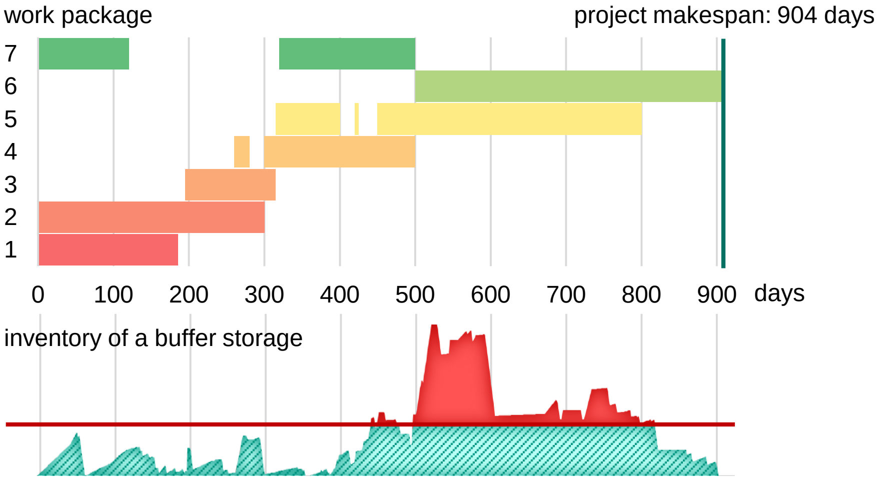


Which are the optimal start and end times of activities so that the **project makespan is minimised** and **resource constraints** and **capacities of buffer storages** are satisfied?

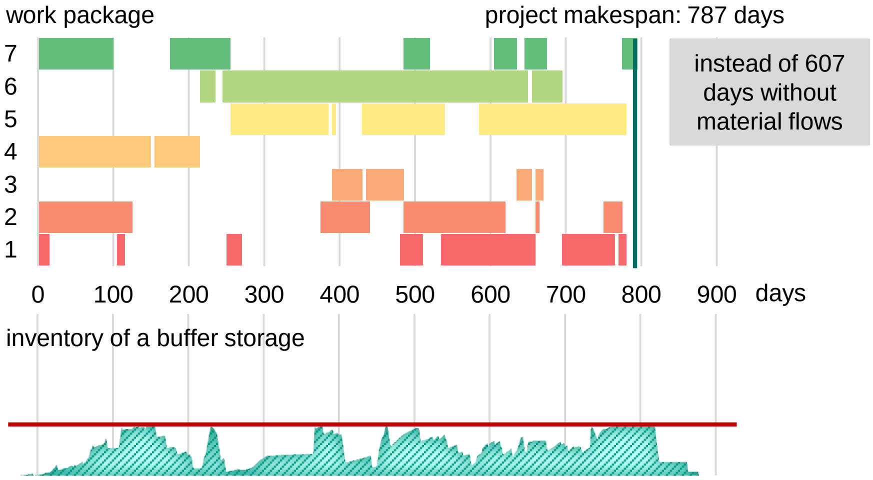
Material flow planning

Optimization results

Critical-path-based scheduling:



Makespan-optimised scheduling:

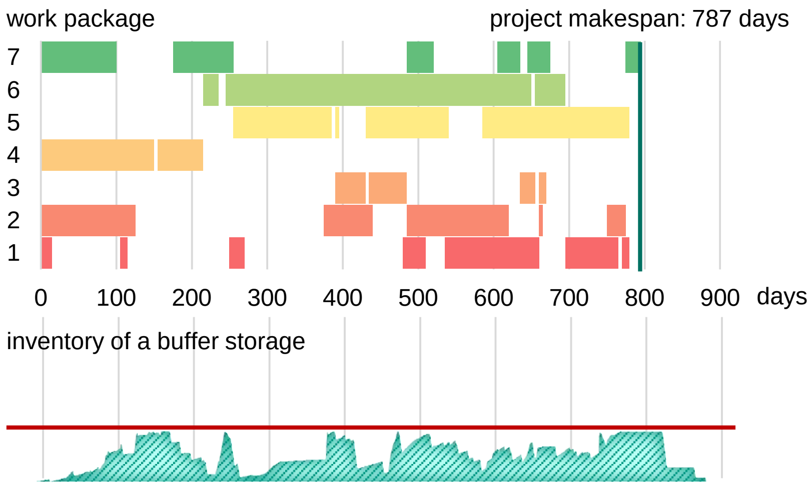


Reduction of project makespan by 117 days (12.9 %) and reduction of buffer storage inventory

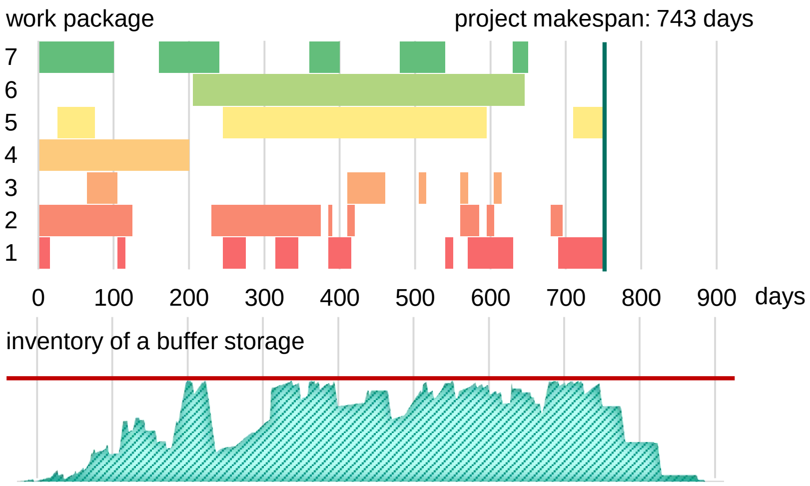
Material flow planning

Scenario analysis

Baseline scenario:



Scenario with **doubled** buffer storage capacity:



Reduction of project makespan by 44 days (5.6 %)

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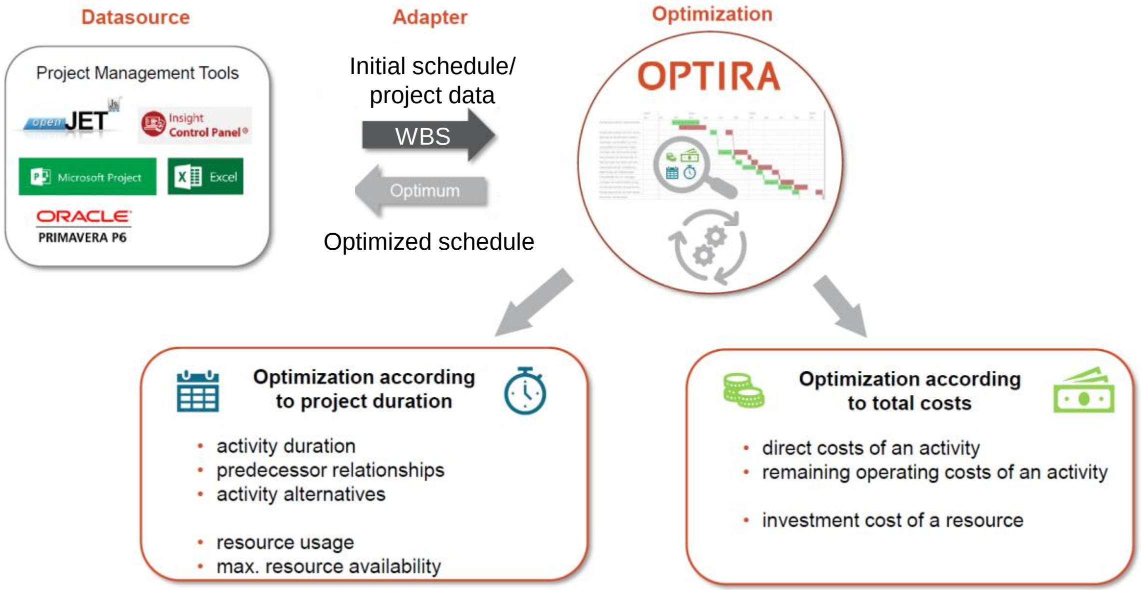
Software OPTIRA

Functionalities

- User-friendly web-based optimisation software
- Import/export interfaces to MS Project, Oracle Primavera and MS Excel
- Minimisation of project duration
- Minimisation of total costs
- Simulation of different szenarios
- Comparison of the original schedule and optimisation results
- Identification, tracking and optimisation of resource and storage load and bottlenecks

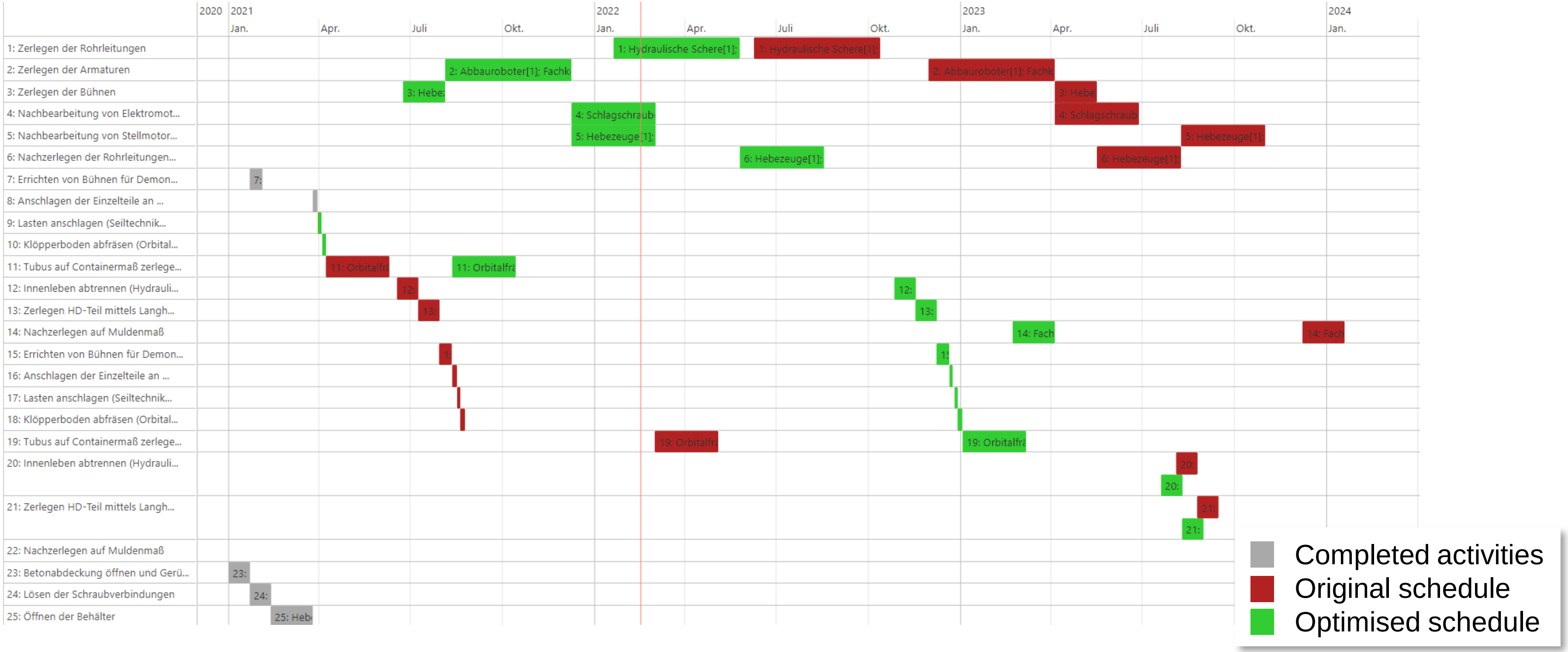


Activity list

Id	Extern Id	Name	Group	Duratio	Finish bonus	Start	End	Predecessor	Ressourceallocation	State	Actions
										Select...	
24712	1	Zerlegen der Rohrleitungen	Beispielprojekt	90	0	09.06.2022	12.10.2022		Hydraulische Schere[1]; Hammer[1]; Hebezeuge[1]; Fachkräfte[4]; Abbauroboter[1]; Kreissäge[1]; Rohrstichsäge[1]; Schlagschrauber[1]; Vorarbeiter[1]	created	
24722	2	Zerlegen der Armaturen	Beispielprojekt	90	0	30.11.2022	04.04.2023		Abbauroboter[1]; Fachkräfte[4]; Schlagschrauber[1]; Hammer[1]; Rohrstichsäge[1]; Kreissäge[1]; Vorarbeiter[1]; Hydraulische Schere[1]; Hebezeuge[1]	created	
24732	3	Zerlegen der Bühnen	Beispielprojekt	30	0	05.04.2023	16.05.2023		Hebezeuge[1]; Rohrstichsäge[1]; Vorarbeiter[1]; Hydraulische Schere[1]; Abbauroboter[1]; Hammer[1]; Schlagschrauber[1]; Kreissäge[1]; Fachkräfte[4]	created	
24742	4	Nachbearbeitung von Elektromotoren	Beispielprojekt	60	0	05.04.2023	27.06.2023	24722	Schlagschrauber[1]; Vorarbeiter[1]; Fachkräfte[1]; Hebezeuge[1]; Hammer[1]	created	
24748	5	Nachbearbeitung von Stellmotoren / Getrieben	Beispielprojekt	60	0	09.08.2023	31.10.2023	24722	Hebezeuge[1]; Hammer[1]; Schlagschrauber[1]; Fachkräfte[1]; Vorarbeiter[1]	created	
24754	6	Nachzerlegen der Rohrleitungen und Bühnen auf Muldenmaß	Beispielprojekt	60	0	17.05.2023	08.08.2023	24712; 24732	Hebezeuge[1]; Hammer[1]; Fachkräfte[1]; Schlagschrauber[1]; Vorarbeiter[1]	created	
24760	7	Errichten von Bühnen für Demontage	Beispielprojekt	9	0	22.01.2021	03.02.2021		Schlagschrauber[1]; Hebezeuge[1]; Vorarbeiter[1]; Fachkräfte[2]; Hammer[1]	closed	
24766	8	Anschlagen der Einzelteile an Abfahrschienen	Beispielprojekt	3	0	26.03.2021	30.03.2021	24760	Rohrstichsäge[1]; Hebezeuge[1]; Fachkräfte[2]; Abbauroboter[1]; Magnetbohrmaschine[1]; Vorarbeiter[1]; Hammer[1]	closed	

Software OPTIRA

Gantt chart



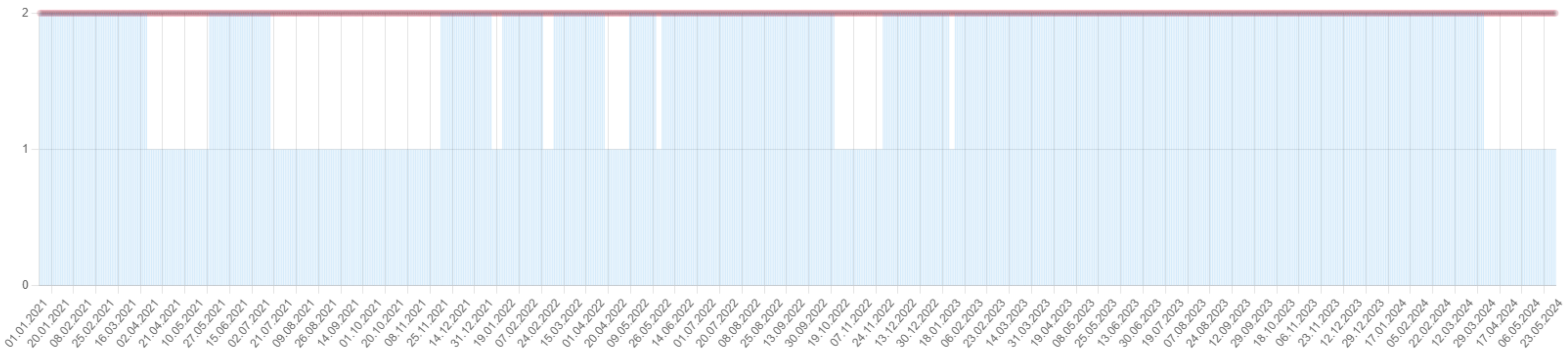
Software OPTIRA

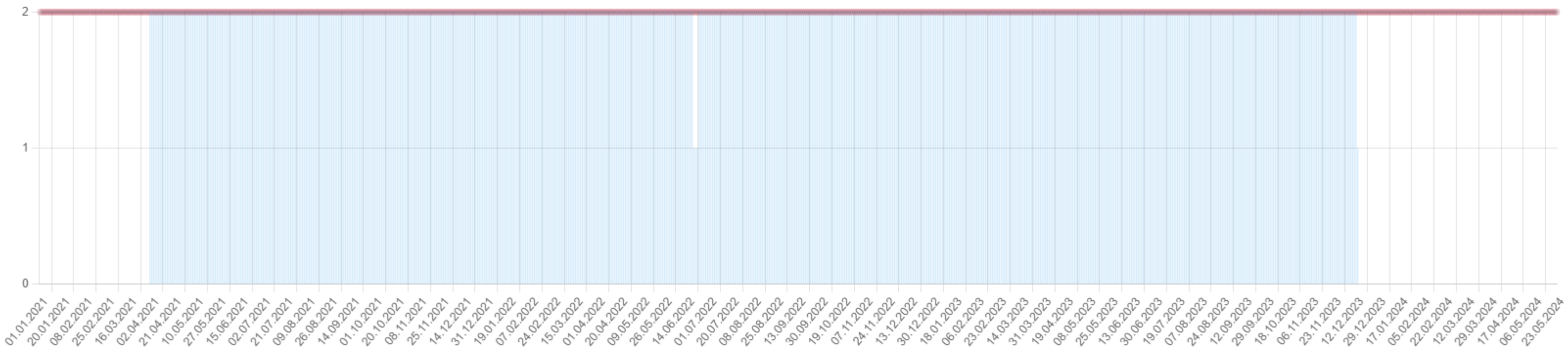
Resource load (1/2)

Name	max. Availability	max. used	Number of max. used	% max. used
Abbauroboter	**2**	**2**	**701**	**99,43 %**
Abstemmgerät	100	2	18	2,55 %
Fachkräfte	20	20	25	3,55 %
Hammer	100	7	3	0,43 %
Hebetechnik Spezialanfertigung	100	1	5	0,71 %
Hebezeuge	100	9	1	0,14 %
Hilfswerkzeug Rotor	100	1	84	11,91 %
Hydraulikpresse	100	1	30	4,26 %
Hydraulische Schere	100	2	104	14,75 %
Kreissäge	100	3	3	0,43 %
Langhubstichsäge	100	8	11	1,56 %
Magnetbohrmaschine	100	8	6	0,85 %
Orbitaldrehmaschine	100	0	0	0,00 %
Orbitalfräse	100	3	16	2,27 %
Plaradschrauber	100	2	6	0,85 %
Rohrstichsäge	100	9	3	0,43 %
Schlagschrauber	100	9	5	0,71 %
Seilsägetechnik	100	1	99	14,04 %
Spezialkran	1	1	196	27,80 %
Vorarbeiter	10	10	5	0,71 %

Software OPTIRA

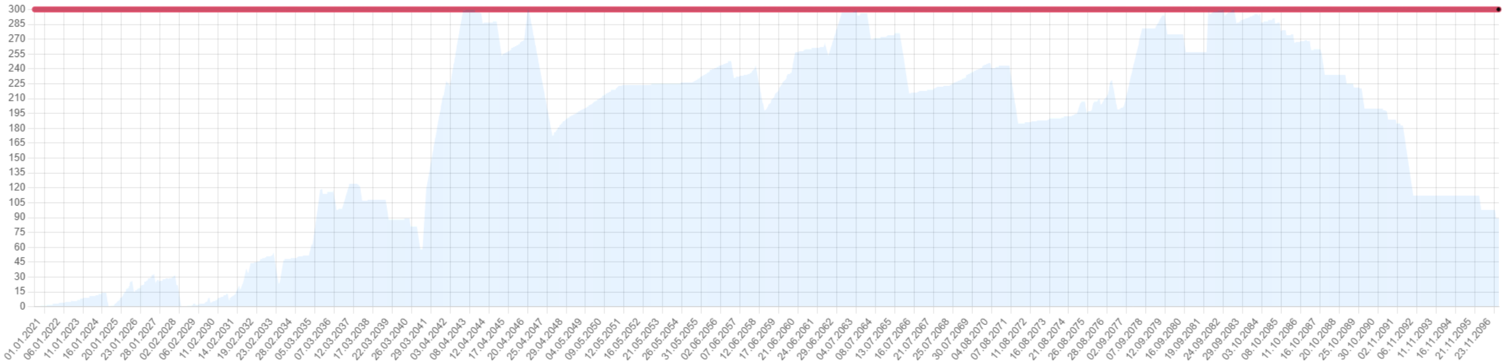
Resource load (2/2)





Software OPTIRA

Storage load



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Conclusion and outlook

A new material flow-based optimisation tool for nuclear decommissioning planning

Benefits

- Considerable saving potentials in project duration and costs via mathematical optimisation
- Identification of material processing and storage bottlenecks
- Tested on real-world data
- Interfaced with MS Project, Oracle Primavera and MS Excel
- Transferable and applicable to all kinds of small and particularly large-scale projects

Data requirements

- Work breakdown structure
- Information about resource requirements and capacities
- For material flow planning: information about released materials and processing paths

Outlook

- Refinement of solution algorithms
- Work on intralogistical and packaging problems in nuclear dismantling (confined spaces, radioactivity, bin packaging)

Thank you!

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Prof. Dr. Frank Schultmann