

# A Control Model for the Dismantling of Industrial Plants

Florian Mach, Eric Hund, Malte Stonis

**Abstract**—The dismantling of disused industrial facilities such as nuclear power plants or refineries is an enormous challenge for the planning and control of the logistic processes. Existing control models do not meet the requirements for a proper dismantling of industrial plants. Therefore, the paper presents an approach for the control of dismantling and post-processing processes (e.g. decontamination) in plant decommissioning. In contrast to existing approaches, the dismantling sequence and depth are selected depending on the capacity utilization of required post-processing processes by also considering individual characteristics of respective dismantling tasks (e.g. decontamination success rate, uncertainties regarding the process times). The results can be used in the dismantling of industrial plants (e.g. nuclear power plants) to reduce dismantling time and costs by avoiding bottlenecks such as capacity constraints.

**Keywords**—Dismantling management, logistics planning and control models, nuclear power plant dismantling, reverse logistics.

## I. INTRODUCTION

THE dismantling of disused industrial facilities such as nuclear power plants or refineries is significantly different and even more complex than the demolition of conventional buildings such as office buildings or houses designed for a single family. The complexity is resulting from a higher, non-specific component range with widely varying work contents as well as the radiological impact of dismantling objects and the required post-processing processes. Unlike conventional disassembling projects, dismantled components have to pass through post-processing processes (e.g. decontamination) which are subject to strict legal regulations. In the post-processing, capacity utilization, stocks, and lead time are significantly depending on the dismantling sequence and depth. Since dismantling sequence and depth can be adjusted within certain limits, the logistical performance in plant decommissioning can be influenced by control models. However, existing control models either do not consider this dependence between dismantling and post-processing processes, or disregard the individual characteristics of dismantling tasks (e.g. flexibility within a specific time period). Disregarded characteristics or an insufficient coupling of dismantling and post-processing processes can cause significant logistical shortfalls such as high stocks or long lead

times. Before a control model for the combined control of dismantling and post-processing processes is introduced, decommissioning specific influences on a control model and existing approaches are analyzed in the following sections.

## II. DISMANTLING OF INDUSTRIAL PLANTS

For an appropriate dismantling control, the basic characteristics of industrial plants have to be analyzed in a first place. Due to the high economic importance as well as the potential to be expected, the basic analysis takes place using the example of nuclear facilities. However, the results can also be transferred to the dismantling of related industrial facilities, such as refineries or chemical plants.

### A. Dismantling and Post-Processing Processes in the Dismantling of Nuclear Facilities

Whereas the dismantled objects of conventional demolition projects can usually be supplied directly to the material cycle or a landfill, the objects of nuclear facilities must first undergo additional process steps for release from the legally prescribed radiation monitoring or for permanent disposal. The process steps relevant for the disassembly control are schematically represented in Fig. 1.

The *disassembly preparation* precedes the actual dismantling steps. Through studies of material composition and radiological properties, the handling expense and route is determined by post-processing within the scope of disassembly preparation. As part of the *disassembly*, all materials, objects, and equipment that are located within the controlled area of a nuclear power plant will be disassembled and broken down into their individual components. Examples of dismantling techniques are rotary tillers, jackhammers, or nailers. If the accessibility to the objects to be disassembled is difficult, additional handling equipment will be used for the disassembly, such as scaffolding, robots, or fork lifts.

The coupling of disassembly and post-processing can generally be done, directly or indirectly, via buffers (see [1]). The indirect coupling with a functional buffer is shown (buffer 1 in Fig. 1). The advantage of functional buffers compared to the direct coupling lies in the spatial relief of the disassembly. This usually has the disadvantage of a higher area requirement.

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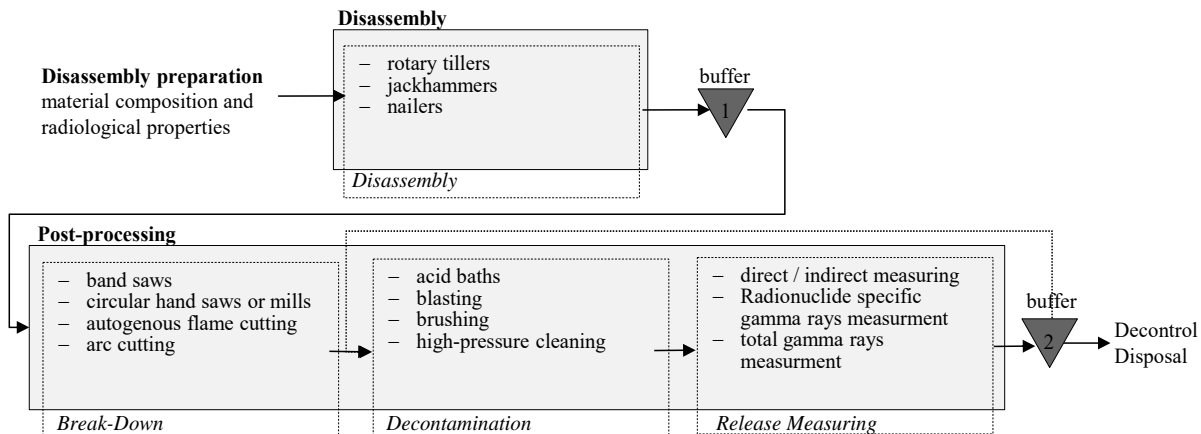


Fig. 1 Process steps in the dismantling of nuclear power plants

As part of the so-called *post-processing*, the disassembled objects are first dismantled, decontaminated, and then measured for release from the legally prescribed radiation monitoring (or for final disposal).

As part of the *Break-Down*, the disassembled objects are broken down into sizes (such as furnace size) and weight that are manageable for the staff and the subsequent technologies. For objects with a low surface accessibility, it is also ensured that the subsequent treatment steps can be carried out properly and with little effort. Various thermal and mechanical breakdown techniques have proven effective in the breakdown of different disassembly objects. Examples of mechanical processes are band saws, circular hand saws, or mills. Thermal processes include, among others, autogenous flame cutting or arc cutting.

The aim of *decontamination* is to reduce the mass of the materials requiring final disposal to the smallest degree possible and to minimize the radiation exposure for staff. For this purpose, the dismantled and broken down objects are freed of solid or loosely adhering contamination through chemical or mechanical removal methods. Acid baths (such as sodium hydroxide), for example, are used as a chemical decontamination method. The mechanical removal of contamination occurs, for example, via sand blasting, brushing, or high-pressure cleaning (e.g. with water).

In the last step, *release measurement*, a decision is made as to whether an object can be released from the legally prescribed radiation monitoring and recycled or reused or whether it has to be disposed of as conventional construction waste. The limits of the adhering radionuclide of an object are decisive for this. Objects that do not meet the release criteria must be returned to decontamination or disposed of as radioactive waste [2], [3].

The specific selection of breakdown and decontamination technologies depends on the nature and composition of the resulting masses and is made with respect to the technological performance values and the (contaminated) waste associated with a technology. Depending on the type of reactor (pressurized water, boiling water reactor), the reactor power and the respective decommissioning phase, the masses and range of components, however, may sometimes vary

considerably with respect to the resulting masses and the material composition.

#### B. Range of Components in the Dismantling of Nuclear Facilities

The range of components to be dismantled in the dismantling of nuclear facilities includes all materials, objects, and plant items that are located in the controlled area of the nuclear power plant. Examples are concrete structures as well as motors, pumps, heat exchangers, or any type of cable. The resulting masses are primarily objects with little to no repetition rate for which there is only little unclear information (e.g. about specific mass distribution) available from the disassembly preparation at the start of disassembly. The objects differentiate among themselves with respect to the process steps that are required for the release from the legally prescribed radiation monitoring or final disposal as well as the resulting processing times at the individual work stations.

TABLE I  
FACTORS INFLUENCING THE PROCESS STEPS IN THE DISMANTLING OF NUCLEAR POWER PLANTS

| Disassembly                    | Break-Down              | Decontamination         | Release Measuring              |
|--------------------------------|-------------------------|-------------------------|--------------------------------|
| material properties            | material properties     | object surface          | surface to be release measured |
| type and number of connections | cut surface             | contamination intensity |                                |
| accessibility                  | contamination intensity | material properties     |                                |
| contamination intensity        |                         |                         |                                |
| dimensions, weight, geometry   |                         |                         |                                |

Table I assigns the main influencing factors on the processing content to the process steps. Factors that affect all process steps are the object dimensions, the associated weight, and the object geometry. With increasing dimensions and weight, the object handling thus occurs exclusively via handling systems, such as fork lifts or crane systems, whose installation and setup require additional time. The geometry (such as pipes, plates, profiles), in addition to the required process steps, above

all determines the accessibility to process-related points, such as connections (disassembly) or undercuts (decontamination/release measurement).

In addition to the object weight and dimensions, factors that affect the disassembly are, for example, material properties such as hardness, strength, density, coatings, or any type of additives in the material that affect the performance of decontamination systems. Furthermore, the types and number of connections as well as their condition as a result of deterioration (e.g. from wear, corrosion) are decisive for the disassembly steps and times. If the objects to be disassembled are difficult to access (e.g. under water, height), measures that simplify the accessibility are first to be taken. These include, for example, the construction of scaffolding as well as the installation of remote-controlled robots. In addition, supplementary measures for radiation protection are to be taken with increasing contamination intensity or dose output of objects.

Factors that affect the breakdown are the required cut surface as well as the material properties of the object to be dismantled. The type and duration of the breakdown may also vary with the contamination intensity. To minimize the radiation exposure to the staff, the breakdown occurs optionally remote-controlled or under water in the event of heavily contaminated objects [2].

The main influencing factor for decontamination is the object surface to be decontaminated. Furthermore, the type and duration of the decontamination are determined by the contamination intensity or the dose output. At higher dose outputs, a pre-decontamination is usually required to minimize the radiation exposure to staff. The material properties (especially the hardness) influence the decontamination in turn over the required time for the residual removal of adhering contamination (e.g. sandblasting, acid bath). The number of required blasting passes when sandblasting, for example, increases with the material hardness.

Factors that affect the release measurement are the surface to be release measured, but also the geometry, or accessibility to undercuts or holes that have to be release measured.

In its entirety, the range of components is composed of complex individual objects with high variances with respect to the required process contents and times. The effort to determine exact process contents and times is great due to the high level of complexity and variance. As a result, process contents and times are only estimated roughly and with great uncertainty.

### *C. Deficits of DSP in the Dismantling of Nuclear Facilities*

Methods of disassembly sequence planning and control (DSP) currently do not sufficiently take into account the peculiarities of complex disassembly projects (process steps and range of components) with a unique character. On the one hand, the interactions between a spatially restricted disassembly and a subsequent post-processing on site are not sufficiently shown as part of the DSP (deficit 1). On the other hand, the complexity of the individual objects to be dismantled is not

sufficiently taken into consideration as part of the control-related decisions (deficit 2).

Fig. 2 shows the effects of a lack of logistical control in the dismantling of nuclear facilities using the example of the throughput diagram of a workstation of post-processing (such as breakdown). The cumulative input and output curve of post-processing orders to or from a workstation in post-processing is shown. To visualize the throughput time TTP, the associated throughput element for each completed post-processing order is included in addition to the input and output curve. The throughput elements of post-processing orders are sorted according to the completion date (shopfloor-calendar day (SCD)). These elements represent the passage of an order through the workstation [4]. The two-dimensional throughput elements visualize the throughput time TTP in the horizontal, which corresponds to the sum of the inter-operation time TIO and the operation time TIO. In the vertical, the elements visualize the workload (WC) of the orders at the corresponding workstation. Using the throughput elements, statements can be made regarding the handling behavior of a workstation. While some orders are processed immediately after entering the workstation, other orders are postponed (e.g. due to set-up or cleaning restrictions) and have long waiting and throughput times [4]. Furthermore, the throughput elements can be used for visualizing the product structure. It can therefore be seen, among other things, that some orders are divided into several partial orders (e.g. due to the size of orders, number of transport units), whose throughput through the following workstations is independent of each other. Dividing up an original object and transporting to different sinks for further processing results in a 1:n or m:n relationship during disassembly.

The input curve and throughput elements show that fluctuating throughput times of the system objects from disassembly and a high variance with respect to the throughput times of the workstations of post-processing lead to alternating capacity bottlenecks and underutilization situations. Since the usable capacities are limited by spatial restrictions or can only be expanded with great effort, capacity bottlenecks lead to high stocks. With respect to the spatial restrictions, the significance of these stocks is all the greater, since the disassembly itself can be limited by material backlog (dismantling time overall is longer) and causes a considerable effort for the material handling.

If underutilizations occur due to material flow break-ups, this may lead to utilization losses in the post-processing workstations (input higher than output). This is all the more serious, since the maximum operating time of the employees in the security area is coupled to so-called dose limits, i.e. a maximum radiation exposure. Upon reaching these limits, the employees may not be exposed to any further radiation. Employee capacities are eliminated upon reaching these limits or have to be replaced in an expensive manner, which is why maximum productivity is sought after during the deployment period.

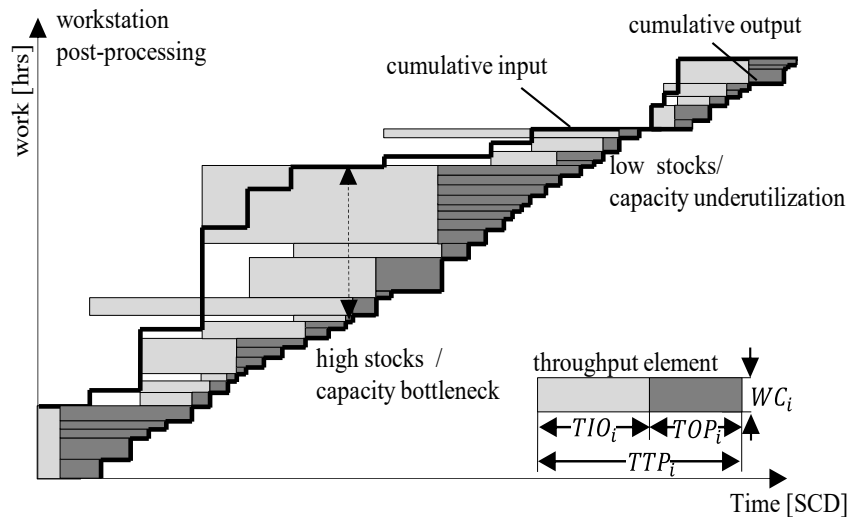


Fig. 2 Throughput diagram of a workstation in the post-processing

### III. EXISTING APPROACHES TO DISASSEMBLY PLANNING AND CONTROL

The following analyzes the extent to which existing concepts from the topic area of DSP make a control of disassembly and post-processing processes possible in plant decommissioning. For this purpose, work from the topic area of DPC is first examined specifically in the dismantling of nuclear facilities before moving on to existing work from the area of DSP in the dismantling of conventional buildings. Since DSP approaches for conventional products in principle can also offer functionalities for controlling in plant decommissioning, existing work from the area of conventional products is then analyzed for the controlling of disassembly and post-processing processes in plant decommissioning. The structuring of these approaches is done accordingly to the functionalities that are serviced by these DSP approaches [5]. Functions relevant to controlling disassembly and post-processing processes in plant decommissioning are *disassembly scheduling*, *resource and capacity planning* as well as the *determination of specified times*.

#### A. Approaches of DSP in the Dismantling of Nuclear Facilities

Numerous DSP approaches in the dismantling of nuclear facilities focus on the *disassembly scheduling*. The presence of an efficient disassembly scheduling for a nuclear facility is a prerequisite for identifying and controlling interactions with the post-processing. Starting from a dismantling model consisting of disassembly, handover buffer, and post-processing, [6] formulates the problem of dismantling scheduling for nuclear power plants in the form of a resource-limited project planning model with renewable and cumulative resources (such as craftspeople, engineers), general term relationships and multiple execution modes. Considering the sequence, capacity, and space constraints (such as buffer size), the method is able to precisely solve problem instances with up to 50 operations in a reasonable time. Although real dismantling projects are

characterized by a much higher number of operations, the basic approach can be used for the load leveling in plant decommissioning.

The *capacity and resource planning* based on knowledge-based methods is discussed in [7]. For this purpose, empirical knowledge from past dismantling projects is structured as part of a database system and is processed for the time, resource and cost calculation in the dismantling of nuclear facilities. Using the system, the dismantling duration as well as the required disassembly capacities and the dose outputs to which the staff are exposed can be estimated in advance.

The *planning of specification times for disassembly operations* represents another task of approaches of DSP in the dismantling of nuclear facilities. In the approach of [8], the component and process information is transferred into a 3D model (3D CAD and virtual reality). A more accurate assessment of the work load and times as well as the resulting radiation exposure for employees is made possible by the 3D simulation of dismantling processes.

The work of [9] presents a model for the efficient process selection when dismantling massive concrete structures in nuclear facilities. The model consists of three components: a requirement component, a knowledge component, and a decision component. As part of the decision component, approaches for the deterministic *determination of disassembly times* are presented on which the procedure selection is based.

In the field of DSP for the dismantling of nuclear facilities there are individual procedures with promising features. However, none of the existing approaches offers a comprehensive image of the interactions between the disassembly and post-processing processes (deficit 1). The approaches essentially deal with mathematical optimization problems in the field of planning. If deviations from the initial plan occur due to faults or technical control decisions, a new solution must be determined with great effort.

### B. Approaches of DSP in the Dismantling of Conventional Buildings

An approach to the environment-oriented *scheduling* in the dismantling of conventional buildings is presented in [5]. Disassembly activities are planned by the optimization approach such that recycling aspects result in beneficial material flows by type and mass. The optimization problems take into account, among other things, capacity restrictions in the disassembly and environmentally-oriented recycling specifications. In [10], a computerized concept is developed for the maximization of contribution margin of disassembly and recycling processes. Based on a preceding structure analysis, the disassembly and preparation steps are inclusively planned while considering technically induced sequence restrictions. Based on the findings from the integral linear optimization model, strategic guidelines for the building demolition were derived.

The planning of specification times for *dismantling operation* is discussed in [11] among others. Using a computerized planning system, individual building information is recorded at the level of individual components and planned on the basis of a heuristic algorithm with respect to minimal dismantling costs and a defined product quality. For this purpose, material flows and expenditure values were balanced and extensive economic characteristics (lead times, mean values, standard deviations) were obtained for the processes of dismantling, sorting and preparation as part of dismantling projects. In principle, the obtained values can also be transferred to the dismantling of complex systems like nuclear power plants.

In the field of dismantling of conventional buildings, existing approaches take into account the planning of dismantling procedures with respect to the distribution of material flows from the disassembly to recycling processes. Capacity-effective interactions, however, are not modeled for the post-processing (deficit 1).

### C. Approaches of DSP in the Disassembly of Conventional Products

The modelling of an efficient *disassembly schedule* for conventional products and workstations via Petri nets can be found in [12]. A cost-optimized dismantling sequence, including the allocation of resources, is derived from a hierarchical and modular connection of disassembly processes and resources. Reference [13] shows a procedure for the dynamic process planning of hybrid disassembly systems. The method is based on knowledge based methods, which identify process alternatives in the event of faults or plan deviations. References [14], [15] show a computerized system for disassembly planning while considering labor disassembly systems.

Reference [16] demonstrates a computerized planning tool for *capacity and resource planning* as well as for the planning of specification times. The tool plans manual disassembly processes by using work schedules, which adapt dynamically and adaptively to changing disassembly conditions (such as feasibility of disassembly operation). In addition to the reactive

planning of alternative disassembly sequences, these dynamic-adaptive work schedules are also able to determine the capacity utilization of post-processing processes.

An approach to determine *standard times* in an uncertain data situation in the disassembly of electronic components is shown in [17]. Time-critical disassembly parameters are modeled using fuzzy logic. If sufficient data are available for the fuzzification, the model can also be transferred to the dismantling of buildings. As part of the determination of *disassembly times*, [18] shows another approach for the modeling of the time structure of divergent disassembly processes by means of critical path method (CPM). The critical path forms the temporally longest path of planned activities within a project network diagram. The critical path determines the shortest time possible to complete a project. Therefore, temporal delays on the critical path have a direct effect on the total duration of a project. Critical activities are opposed by activities which have "float". These activities can be postponed without affecting the project duration. The CPM is in particular suitable for the modeling of dismantling operation. Among other things, the CPM is able to map the temporal relationship between the start of a dismantling sub-process and the presence of a component in post-processing.

The approaches mentioned from the field of conventional products, however, are focused on the disassembly of objects with mostly large quantities. The individual characteristics of dismantling tasks in the plant dismantling (deficit 2) and the effects on post-processing processes (deficit 1) are not taken into consideration.

## IV. APPROACH FOR CONTROLLING DISASSEMBLY AND POST-PROCESSING PROCESSES IN PLANT DISMANTLING

With a combined control of disassembly and post-processing processes the logistical performance (e.g. dismantling time) in plant dismantling can be influenced systematically. In particular, with the specific start of disassembly and post-processing orders, delays from the disassembly sequence can be prevented (sub-goal 1) and a constant capacity utilization in the post-processing (sub-goal 2) is obtained. The same applies to the minimization of the buffer stock level (buffer 1) between the disassembly and post-processing processes (sub-goal 3). To this end, existing methods of PPC (especially order generation and release) will be adapted to the specific characteristics of the plant dismantling. Following characteristics are taken into consideration:

- Sequential and technical degrees of freedom and restrictions;
- Spatially restrictions;
- Technically restrictions.

The coupling of disassembly and post-processing processes is done via buffer 1 between disassembly and post-processing. For this purpose, input (from disassembly) and output (to post-processing) are harmonized moderately while taking into consideration dismantling-specific characteristics.

### A. Degrees of Freedom and Restrictions of the DSP in Plant Decommissioning

From a logistical point of view, characteristics are of particular interest with which the input to the buffer as well as the workload for the workstations in the post-processing can be adapted to the available capacities over the time. The considered characteristics can therefore be allocated to the approaches of load flexibility (see [19]). Dismantling-specific characteristics, which support the coordination between the disassembly and post-processing, are summarized under the degrees of freedom. Characteristics that impede this coordination are allocated to the restrictions. Table II contrasts the relevant degrees of freedom for the use of load flexibility with the relevant restrictions (technical sequential, spatial, and technical).

TABLE II  
DEGREES OF FREEDOM AND RESTRICTIONS FOR THE USE OF LOAD FLEXIBILITY IN PLANT DECOMMISSIONING

| Degrees of freedom (F) for the use of load flexibility | Restriction (R) in the use of load flexibility |
|--|--|
| F1. Workload of disassembly and post-processing orders | R1. Available buffer area                      |
| F2. Start times/disassembly sequence                   | R2. Defined disassembly sequence               |
| F3. Dismantling sequences and material treatment paths | R3. Scheduling (latest start/end dates)        |
|  | R4. Set-up and cleaning processes              |

When adjusting the workload (degree of freedom F1), a disassembly order is split into two or more separate sub-orders (with separate transport units). Fig. 3 schematically illustrates the adjustment of workloads. The temporal (in the horizontal) and intensity (in the vertical) outputs of a work order from a workstation (WS) are shown. The left part of the image shows the original output and the right part shows the output with the appropriate workload. By splitting up into several sub-orders with smaller or half workload, the input time and intensity from disassembly to a workstation in the post-processing can be controlled. With an increasing number of generated sub-orders, and therefore decreasing work content per order, the possibility to level the loads on the workstations tends to increase. Since the space requirements (restriction R1) and the logistical efforts both increase with an increasing number of orders, the number of potentially possible sub-orders has to be limited, for example, via the maximum number of transport units.

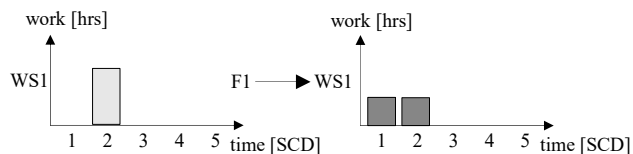


Fig. 3 Effects of adjusted workloads to the capacity utilization

When moving the start times, the start date of a disassembly order is postponed or antedated (degree of freedom F2). Fig. 4 schematically illustrates the moving of starting times. The left part of the image shows the original input from disassembly and the right part shows the output when antedating the starting

time. By moving the disassembly start dates, the temporal input and output of a work order can be controlled. Antedating a disassembly start date is restricted by the disassembly sequence set up as part of the disassembly planning. An order can be antedated as soon as all of its predecessors have been processed (restriction R2). Postponing a disassembly start date is restricted by the latest start or end date scheduled as part of the disassembly planning (restriction R3). Delays beyond the latest start and end dates directly affect the dismantling time. If sequential mix-ups are associated with moving starting times, then sequential restrictions, such as impermissible set-up and cleaning processes, must also be observed (restriction R4).

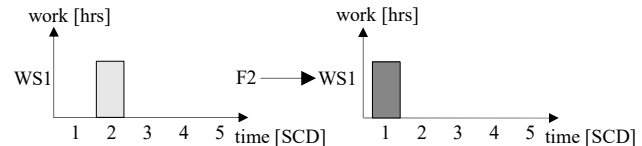


Fig. 4 Effect of moving start times to the capacity utilization

When choosing alternative disassembly processes and material treatment paths (degree of freedom F3), the planned assignment of work operations is canceled and replaced by an alternative. Fig. 5 illustrates the effects on the intensity-related input and output when choosing alternative work systems with free capacities (such as band saws instead of circular hand saws), on which it is possible to execute the required work operations. The left part of the image shows the original output and the right part shows the output on an alternative workstation (WS2) with free capacities. Due to the higher performance of the alternative workstation, the intensity-related load decreases. This may be faced with negative aspects, such as a higher radiation dose or a higher residual material mass. The output date can also be antedated due to the lower load at workstation 2.

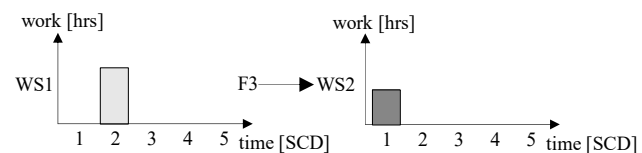


Fig. 5 Effect of alternative material treatment paths to the capacity utilization

### B. Procedural Description

The set-up of the procedure for a combined control of disassembly and post-processing processes is schematically visualized in Fig. 6. The part of the procedure that controls the disassembly should, on the one hand, avoid delays in the dismantling project by the schedule-oriented release of disassembly orders on the critical path (sub-goal 1). On the other hand, the generation and release of orders with float as a function of the capacity utilization should keep the stocks at a consistently low level (sub-goal 3). Therefore input (from disassembly) and output (to post-processing) to buffer 1 are coordinated with each other.

The generation and release of disassembly orders takes place under consideration of dismantling-specific restrictions (R1-R4) and degrees of freedom (F1-F3) in three basic steps:

1.1 Release of critical orders (schedule-oriented order release)

1.2 Reservation of capacities for critical orders in the planning horizon

1.3 Generation and release of orders with total float for load balancing (load-oriented order generation and release)

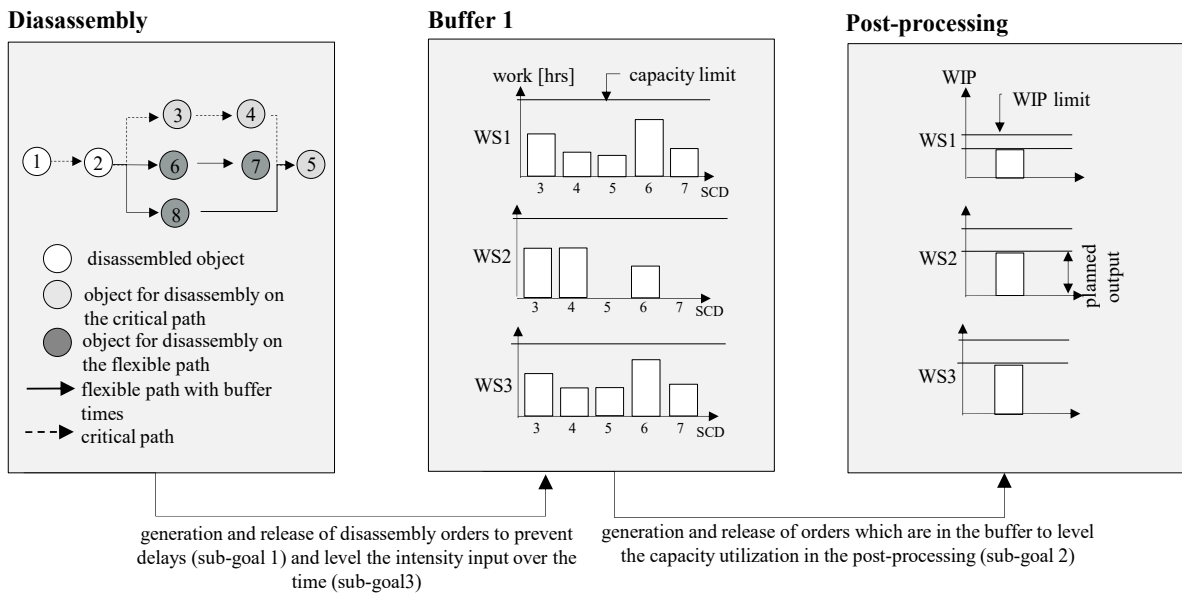


Fig. 6 Procedure steps for the combined control of disassembly and post-processing processes

Based on the project network diagrams, a distinction is made between orders on the critical path and those not on this path when releasing disassembly orders. In the first procedural step (1.1), orders are prioritized which are on the critical path in order to avoid temporal delays of the dismantling project as a whole (sub-goal 1). The release of critical disassembly orders is done according to the *Constant Work In Process (CONWIP)* procedure. The basic idea of this procedure is to keep the stock at a constant level, thereby avoiding delays due to material backlog (sub-goal 1; sub-goal 3). Accordingly, an order is only released for disassembly as soon as sufficient capacities in the buffer are available. To this end, the disassembly order is chosen from the list of critical orders to be released that has the highest priority [20]. The priority is derived from the planned start date in order to avoid delays on the critical path. Therefore, orders with an earlier planned start date have a higher priority. The list of orders to be released contains all of the disassembly orders whose release criteria are met. The release criterion for critical disassembly orders is met once all predecessors have been completely disassembled. This is the case for order 3 in the example shown in Fig. 7.

For all released critical orders, the work content for the post-processing processes is booked in the so-called capacity accounts. Fig. 8 shows the capacity accounts for determining the input over time at buffer 1. Time is plotted in the horizontal, and the forecasted workload for processing at the post-processing workstations is plotted in the vertical. Based on the planned start date, the temporal input at the buffer is determined by forward scheduling.

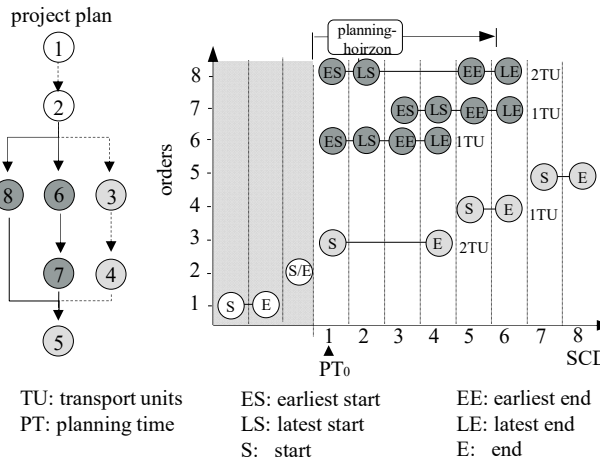


Fig. 7 Exemplary disassembly schedule in plant dismantling

$$T_{input,n} = T_{start} + \sum_{i=1}^n (TOP_{i,j}) + TIO_{n,j} \quad (1)$$

with n: disassembly (sub)order;  $T_{input,n}$ : input time of the (sub)order n at the buffer [SCD];  $T_{start}$ : planned start date of the order [SCD];  $TOP_{i,j}$ : operation time of the (sub)order i at the workstation j [SCD];  $TIO_{n,j}$ : inter-operation time of the (sub)order n at the workstation j [BKT].

The input time  $T_{input,n}$  of a (sub)order n at buffer 1 can be determined via the planned start date  $T_{start}$  plus the disassembly throughput time ( $TOP + TIO$ ). The disassembly throughput time of a sub-order n corresponds to the sum of the operation times of all preceding sub-orders plus the operation time of the considered sub-order and the corresponding inter-operation

time. Since, as a result of the diverging material flow, an uncoupled material transport is possible, each transport unit corresponds to a separate sub-order. The correlation between the number of required transport units and the input of orders at buffer 1 is shown in Fig. 8. The splitting of order 3 into two separate transport units results in two different input times for the sub-orders 3.1 and 3.2.

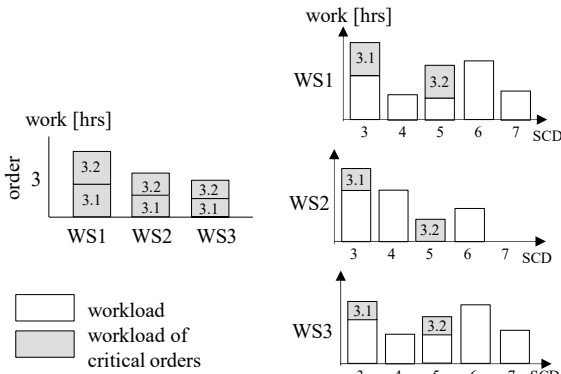


Fig. 8 Capacity accounts for determining the input at buffer 1

In the second procedural step (1.2), the required transport units and capacities for the corresponding post-processing processes are reserved for critical orders whose predecessors have not yet been disassembled. The reservation of transport units occurs within a sufficiently large planning horizon, within which critical orders are taken into account for the following control steps before their actual planned start date. The condition for the identification of critical orders is accordingly:

$$PT_0 + PH \leq T_{start} \tag{2}$$

with  $PT_0$ : planning time [SCD];  $PH$ : planning horizon [SCD];  $T_{start}$ : planned start date of the order [SCD]. This is the case for order 4 in the example shown in Fig. 7. The start date of order 5 is not within the planning horizon and will not be considered further. A transport unit is accordingly withheld for the disassembly of order 4. This is done by booking the required work for the post-processing processes in the accounts at buffer 1 (see Fig. 9).

In procedural step 1.3, orders, which are not on the critical path, are generated and released so that the required capacities for post-processing processes are leveled out over time. Due to this leveling, underutilization situations at the post-processing workstations can be avoided (sub-goal 2, sub-goal 3). The same holds true for the build-up of stock (use of transport units) as a result of overload situations (sub-goal 1, sub-goal 3). The leveling should be done through an adjustment of the buffer input (orders coming from disassembly) to the output (orders going to post-processing). The input to buffer 1 is determined by the release of disassembly orders (procedural section 1). The output is determined by the release of post-processing orders (procedural section 2). To adapt the buffer input to the output, a capacity limit is set, which limits the period-based input of disassembly orders to the buffer 1 as a function of the medium performance in post-processing.

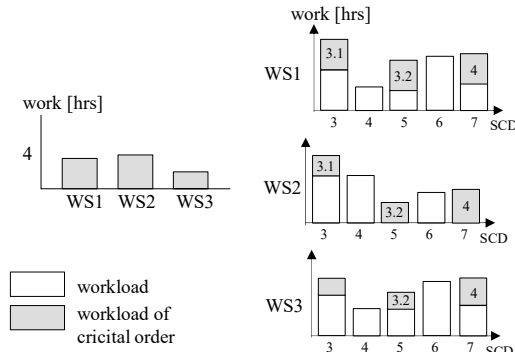


Fig. 9 Reservation of capacities for the treatment of critical orders

In order to avoid delays apart from the critical path, the identified orders are prioritized according to the latest start date. Once the latest start date of an order is reached, it is prioritized like a critical order. The list of orders to be generated and released contains all of the disassembly orders whose release criteria are met. The release criteria for such orders are met, when all predecessors have been processed and the planning time  $PT_0$  is between the earliest  $T_{ES}$  and latest start date  $T_{LS}$ :

$$T_{ES} \leq PT_0 \leq T_{LS} \tag{3}$$

with  $PT_0$ : planning time [SCD];  $T_{ES}$ : earliest start [SCD];  $T_{LS}$ : latest start [SCD].

This is the case for order 6 and 8 in the example shown in Fig. 7. The start date of order 7 is not yet reached. Its predecessor (order 6) was also not yet disassembled. The identified and sorted orders are then generated (scheduling of start time, work content and workstations) by utilizing approaches of load flexibility (degree of freedom F1 - F3) such that the intensity-related input (capacity requirement at the post-processing workstations) at buffer 1 corresponds to the output in the planned period (see Fig. 10). These orders are released when transport units are available and the capacity limits have not yet been exceeded for the required post-processing work operations at buffer 1. The work content is then booked in the capacity accounts in a deadline-bound manner. If the input exceeds the capacity limit, the capacity limit has to be lowered by the corresponding carry-over in the subsequent periods (Fig. 10: AS2; 6. SCD). The dynamic adjustment of workstation-specific capacity limits prevents a stock build-up at buffer 1 between disassembly and post-processing.

The procedural part that controls the post-processing should level the load at the post-processing workstations to a permissibly high level through the release of post-processing orders (orders in buffer 1) (sub-goal 2). The load balancing is done in two steps while using the identified degrees of freedom F1-F3:

- 2.1 Determination of the capacity utilization in post-processing by determining the work progress of released post-processing orders
- 2.2 Generation and release of post-processing orders with a load balancing



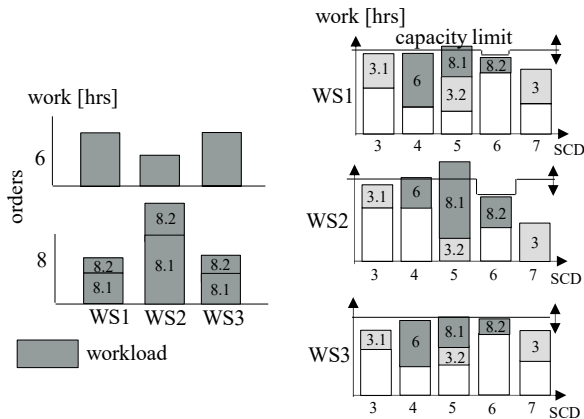


Fig. 10 Leveling of the intensity-related input to buffer 1

As part of the first step (2.1), deviations between the planned and actual output are recorded by determining the work-in-process at the post-processing work stations through already released orders. Uncertainties regarding the determined planned data can thus be taken into consideration and compensated during post-processing. The determined work-in-process at the workstations forms the input data for the second step (2.2). As part of the order generation, the orders in buffer 1 are generated such that the capacity gaps at the post-processing workstations are minimized. The capacity gap is formed by the difference of the work-in-process limits and the actual work-in-process. The total work-in-process corresponds to the work at the workstation itself (direct work-in-process) and the work that is found at preceding workstations (indirect work-in-process). The capacity gap likewise forms the priority indicator according to which post-processing orders are released. The priority indicator of an order is calculated as follows:

$$CAP_{GAP,medium} = \frac{\sum_{j=1}^m (WIP_{limit,j} - WIP_{tot,j} - WC_{Req,i,j})}{m} \quad (4)$$

with  $m$ : number of workstations to be run through;  $j$ : workstation;  $i$ : order;  $CAP_{Gap, medium}$ : medium capacity gap [h];  $WIP_{limit, j}$ : work-in-process limit of the workings system  $j$  [h];  $WIP_{tot,j}$ : total work-in-process of the working system  $j$  [h];  $WC_{Req, i, j}$ : required work content of an order  $i$  at the workstation  $j$  [h].

Post-processing orders are released similar to the *Workload Control* [21], when the WIP limit is not exceeded at the required workstations (Fig. 11, order 1). If the WIP of a workstation exceeds the WIP limit after booking, the release of all post-processing orders that run through the corresponding workstation is blocked [20] (Fig. 11, order 2). Existing approaches to determination of WIP limits can also be transferred to the plant decommissioning (see [22]). In its entirety, the presented approach controls the disassembly as a function of the capacity utilization in the post-processing, while considering dismantling-specific characteristics. Compared to the existing approaches, a systematically influence of the logistical performance can be achieved through coordinated process steps. As a result, dismantling times and stocks can be minimized as well as the capacity utilization at the post-

processing workstations can be leveled out to a permissibly high level.

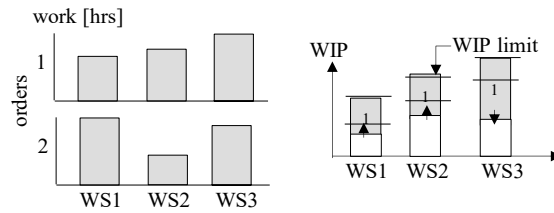


Fig. 11 Leveling the WIP in post-processing through order generation and release

## V. FURTHER WORK

Future work will focus on the validation of the procedure's potential and the identification of the application limits. For this purpose, simulation studies have to be conducted. The question of how much characteristic variables of load flexibility (e. g. average temporal shift of processes or divisibility of orders) are related with the achievement of logistical goals (throughput time of the dismantling project, buffer stocks and capacity utilization of workstations) is another priority for further investigation. At the same time, it should be identified under what conditions the use of load flexibility pushes its limits and the logistical performance of decommissioning is restricted.

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