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Material Disposition and Scheduling in Regeneration Processes using Prognostic Data Mining

Tammo Heuer[a]*, Torben Lucht[a], Peter Nyhuis[a]

[a]Institue of Production Systems and Logistics, An der Universität 2, 30823 Garbsen, Germany

Abstract

In the regeneration process of complex capital goods, the definite workload is uncertain until the goods are disassembled and inspected. Due to the uncertainty and long repair lead times, regeneration service providers have difficulties in achieving low regeneration times and meeting delivery dates. Delays in delivery are associated with contractual penalties and keeping a high stock level of spare parts coincides with a high capital tie-up. Therefore, this paper deals with the use of prognostic data mining for long-term material disposition and scheduling to accomplish a high delivery date reliability and low stock levels.

Keywords: regeneration; complex capital good; material disposition, scheduling

1. Planning regeneration processes under uncertainty

The regeneration of complex capital goods is a comprehensive field for research. Due to high investment costs and the high income within the usage of such machinery subsequently idleness means a huge monetary loss. As a result, the cost saving potential of a smart production planning regarding a low throughput time and delivery reliability in the regeneration is significant [1]. The focus of this paper is therefore on an approach for production planning using the predicted workloads for material disposition and scheduling with the aim of achieving the mentioned target criterions.

Regeneration distinguishes from production processes by a couple of key differences. Complex capital goods come with a high number of individual components, where many parts are susceptible to wear while others are less impaired by usage. The purpose of regenerating these goods is adding value by prolonging their service life [2]. The required

* Corresponding author. Tel.: +49-511-762-18187; fax: +49-511-762-3814.
E-mail address: heuer@ifa.uni-hannover.de

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regeneration measures are not necessarily known at the beginning of the regeneration process. While the rough damage pattern can already be estimated before physical induction in the work shop, a comprehensive inspection after the disassembly is required to identify the damage to an individual component [3]. Thus, the planning of regeneration processes is shaped by uncertainty in information. There is no precise information about which components of the complex capital goods are scrap, damaged (non-serviceable or short nSA) or serviceable (SA). These uncertainties lead to difficulties in planning capacity and material demands. Results are long regeneration throughput times and delivery lateness which are opposed to high requirements regarding the adherence to delivery dates by the customers [4, 5].

Due to the progressing digitalization more data is available on the complex capital goods but also on their surroundings. E.g. transformers even in remote areas are constantly online and communicate key values like oil temperature or voltage. In aircraft turbines data of process values have always been accumulated in the turbine's computer [6]. With recent high interest in data-mining and machine learning new approaches of forecasting the components' damage pattern and through this the estimated workload are tested on the obtained data. They offer the possibility to do a more precise production planning. There is still an uncertainty, but like shown in Fig. 1 the accuracy of information is already on a higher level before the good reaches the disassembly [7, 8].

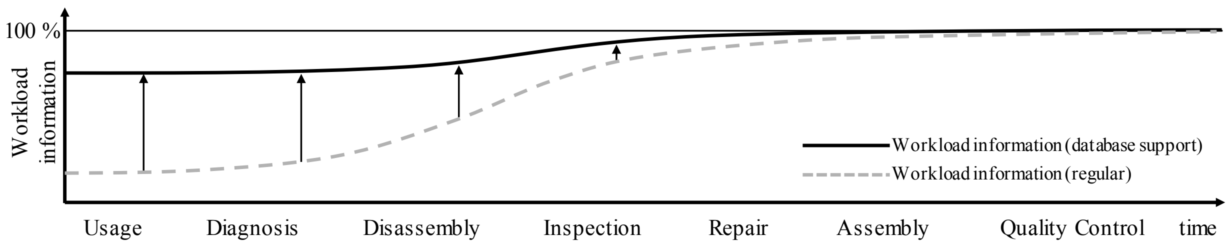


Fig. 1. Increasing accuracy of information in the regeneration process [9]

2. State of regeneration processes of complex capital goods

Complex goods may either be sent to maintenance because the elapsed active times has reached a maintenance interval or because of a case of damage [10]. Like mentioned above, a rough diagnosis is made prior to physical induction based on information of previous similar regeneration orders and information gathered on the individual good [7, 11]. This diagnosis either leads to a full or partial disassembly of the capital good. The disassembled components are then sent to inspection where they undergo a standardized and detailed analysis on the degree of damage. Only from this point on a precise assessment of the actual damage pattern is available so that required regeneration measures can be planned. The late certainty of the anticipated workload is a key difference compared to normal manufacturing [12].

Consequently, the repair process of the components is being conducted. A large part of the regeneration throughput time is spent on the repair [11] and for this reason the repair is usually a time-critical part of the regeneration [12]. Therefore, the challenge is to lead parallel regeneration orders simultaneously and punctual through the repair [13]. After the repair processes, all components converge during assembly and the regenerated capital goods are subjected to quality control. The availability of all required components for assembly is of particular importance for on-time delivery of the regenerated capital good. Especially capital goods with many components requires a well-planned logistic procedure [14, 15]. Higher than the estimated damage pattern and unexpected incoming repair orders as well as special customer requests can significantly influence the workload and have to be taken into account for production planning [16].

A design option to compensate these uncertainties is pooling. In order to reduce the risk of material shortages and thus a delayed delivery, a regeneration service provider maintains a stock of most commonly processed components. Generally, they can be discerned between nSA-Pools and SA-Pools. Non-serviceable components are stocked in the nSA-Pool, when there is no capacity available to be repaired. Components that already have been repaired and made serviceable but have not been needed for an assembly are stored in the SA-Pool [12].

3. Simultaneous material disposition and scheduling

Available capacity is usually also limited, so that if workload is too high, bottlenecks can occur along the regeneration supply chain. This leads to longer throughput times and thus to non-adherence to agreed delivery dates which is closely tied with contractual punishments [17]. Thus, this paper is about a production planning approach using the prediction of anticipated workloads for material disposition and scheduling.

3.1. Process elements and related time elements

To introduce the material disposition problem the following section defines the process elements and the relevant related time elements of a regeneration process. A simplified example is illustrated in Fig. 2.

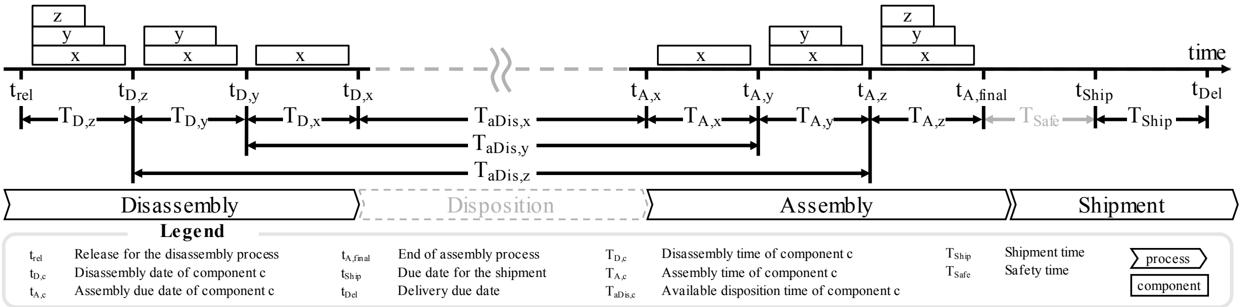


Fig. 2. Disassembly and Assembly Process and Times

During the disassembly the capital good is split into its components c ϵ C. C forms the set of different components (e.g. x, y and z). When the capital good gets released for the regeneration process at t_{rel} the disassembly process starts with the removal of the outer component z. After a disassembly time $T_{D,z}$ the component z is disassembled and available for the disposition in the moment $t_{D,z}$. Simultaneously the disassembly of component y starts. This process continues until the last component x gets released for disposition. Various sources for the material disposition will be explained in chapter 3.2.

This paper only considers a successive strategy, in which the single components are disassembled from the outside to the inside (1.z – yx; 2.y – x). If the capital good's constructional structure allows, alternative strategies (e.g. 1.zy – x; 2.z – y) could be integrated. The described example would enable an earlier availability of the inner component x, because the outer components z and y are disassembled as a couple.

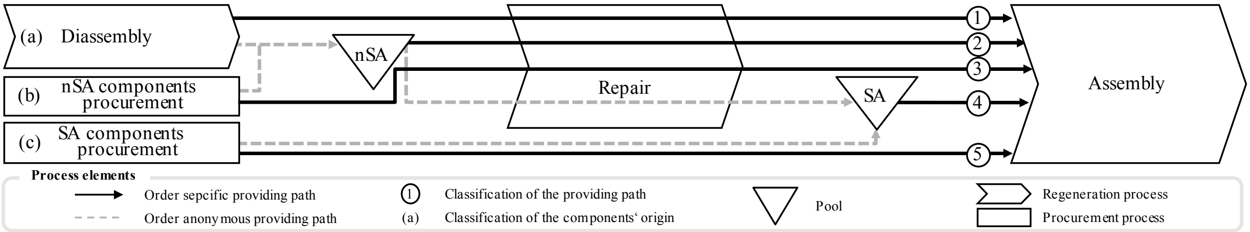
To analyse the time elements of the assembly and the shipment the agreed delivery due date t_{Del} of the regenerated good is considered. The latest date to ship the good, the shipment due date t_{Ship}, is the delivery due date t_{Del} minus the shipment time T_{Ship} from the service provider to the customer. In addition, a safety time T_{Safe} could be added to buffer fluctuations in the regeneration process and assure an on time delivery [18]. The shipment due date t_{Ship} and the safety time T_{Safe} lead to the final assembly due date $t_{A,final}$ of the capital good being repaired and completely assembled. Taking assembly times $T_{A,c}$ into account, a backward scheduling results in the assembly due dates $t_{A,c}$ for the different components. This represents the latest time for the components to be provided by the material disposition as well as the latest time to start the component's assembly. After the component c has been disassembled at $T_{D,c}$ the maximum available time for the component to go through the repair process and to be provided for reassembly, the available disposition time $T_{aDis,c}$, is calculated as the following:

$$T_{aDis,c} = T_{A,c} - T_{D,c} \tag{1}$$

In the case of the successive disassembling strategy this leads to the conclusion, that the outer components have a longer disposition time than the inner components.

3.2. Material disposition paths

There are several options for providing the components for assembly when required at tA,c. Possible paths p ϵ P for disposition are shown and differentiated in components' origins in Fig. 3.



	Providing components from				
Components' origin	(1) Repair	(2) Repair	(3) Repair	(4) SA-pool	(5) SA comp.
(a) Disassembly	1a	2a		4a	
(b) nSA component procurement		2b	3b	4b	
(c) SA component procurement				4c	5c

Fig. 3. Disposition paths in regeneration processes

After the disassembly for every non-serviceable component a path to meet the assembly due date has to be selected. The most common path is represented by 1a. The disassembled component gets repaired and provided for the assembly. In path 2 nSA components of the nSA-pool are used. These can originate from the disassembly of other goods (2a) or have been procured via an nSA procurement (2b). In contrast to path 2b the nSA components can also be procured directly to get repaired and assembled in the considered good (3). Paths 2a, 2b and 3 offer the opportunity to replace severely damaged components with nSA components that are less damaged and thus reduce the throughput time through repair. Serviceable components can be provided from the SA-pool (4) or through individual procurement (5). In case of procuring an nSA component with lower damage pattern (2b) or a SA component (5) an additional procurement lead time has to be considered.

The different paths are characterized by varying disposition times $T_{Dis,p}$. These are elementary for the choice of the paths and dependent of a variety of variables. The main elements of the disposition time are:

- the waiting time T_w of a repair job in a buffer in front of the repair depending on the buffer stock bs and its priority pr within the waiting orders,
- the repair lead time T_{Rep} depending on the damage pattern dp and
- the procurement lead time T_{pr}.

Other variables, which have to be considered are the damage pattern dp_{nSA} of the components in the nSA-pool and the damage pattern $dp_{nSA,pr}$ of a procurable nSA component. Neglecting time elements such as intern handling, which are relatively small compared to the described main elements, the disposition time per path is defined in the following:

$$T_{Dis,1a} = T_w(bs,pr) + T_{Rep}(dp) \tag{2}$$

$$T_{Dis,2a} = T_{Dis,2b} = T_w(bs,pr) + T_{Rep}(da(nSA)) \tag{3}$$

$$T_{Dis,3b} = T_w(bs,pr) + T_{Rep}(dp_{nSA,pr}) + T_{pr} \tag{4}$$

$$T_{Dis,4a} = T_{Dis,4b} = T_{Dis,4c} = 0 \tag{5}$$

$$T_{Dis,5} = T_{pr} \tag{6}$$

3.3. Regeneration scheduling

After the components have been disassembled, the disposition time differs with regard to the chosen disposition paths and production control processes. The waiting time of repair orders in the buffer in front of the repair is dependent on the buffer stock and the priority given by the production control. A common method to determinate priorities is the use of priority rules like first-in-first-out (FIFO), shortest operation time (SOT) or earliest planned start date (ESD). The FIFO-rule assures that no changes in the sequence are done. Thus, the deviation of plan can be kept to a minimum. The SOT-rule prioritizes the order with the shortest operating time. In the short term, this leads to a low average throughput time, but the variance in throughput time increases [19]. The application of the earliest planned start date (ESD) rule allows the compensation of deviations between planned and due dates accelerating late orders. As a result, this rule improves due date reliability [20]. The positive effect using ESD in regeneration supply chains has already been proven in another simulation study [21]. Due to the high requirements regarding due date reliability in regeneration the ESD-rule will be used for the following considerations of regeneration scheduling.

With N as the set of orders in the buffer in front of the repair, every order $n \in N$ has a disposition due date $t_{Dis,n}$ in order to be available on time for assembly. This date equals the assembly due date $t_{A,c}$. Furthermore, the orders have a repair lead time $T_{Rep,n}$. Using these parameters, the planned start date is calculated as the following:

$$sd_n = t_{A,n} - T_{Rep,n} \tag{7}$$

The calculation of the priorities and the subsequent scheduling are illustrated in Fig. 4. After the prioritization (1.) the orders are scheduled (2.). As shown, bottlenecks causing lateness of orders can be identified.

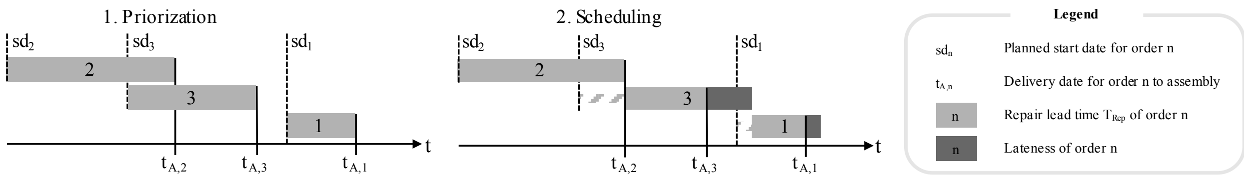


Fig. 4. Usage of the ESD-rule for regeneration scheduling

Due to such bottlenecks for some orders alternative material dispositions paths than the one through the repair can be chosen to avoid lateness. Doing this several restrictions have to be considered. Path 2 needs a stock of nSA components of the specific component with a lower damage than the considered component to allow a repair lead time reduction. nSA components with less damage could also be procured (3b), but in this case a procurement lead time has to be added to the order's disposition time. The usability of path 4 is restricted by the stock of SA components in the SA-pool. Both the nSA and SA stock are limited due to the stock holding costs and warehouse capacity. For path 5 the procurement time T_{pr} has to be considered. Taking into account these restrictions each path has to be chosen with an accurate disposition time $T_{Dis,p}$ which is lower than the available disposition time $T_{aDis,c}$ or equal to avoid lateness to assembly.

4. Conclusion

This paper describes two main decisions to make for planning the regeneration of complex capital goods. On the one hand there is the selection of material disposition paths. On the other hand there is the scheduling of the single repair orders. Both decisions have strong dependencies between each other and have a lot constraints to consider.

If a material disposition path is not selected until the component has just been disassembled and inspected, the reaction options are limited. Often the disposition time (including the procurement time) is longer than the available disposition time. This problem may be solved by holding an inventory of the specific component in the SA-pool, though inventory is accompanied with capital costs.

The dependencies between the pool stock and the missing components situation during reassembly allows a logistical positioning between high stock costs, a high service level and a high due date reliability [13]. Nevertheless, the use of this relation would not consider workload predictions to adapt the stock dynamically. Thus, the use of workload predictions enables a production planning in advance, before the complex capital goods reach the disassembly. With the predicted workloads future repair utilizations can be anticipated by the approach of chapter 3.2 and 3.3. Dependent on bottlenecks and on an expected stock development the stock level could be regulated dynamically through filling the SA-pool by the procurement or the repairing of nSA-components from the nSA-pool. The stock can be at a higher level than a fixed stock when demand is high. Conversely, stock may be lower if predicted workload is low and there is sufficient repair capacity. Consequently, this approach has the potential to achieve a lower average stock level while providing a higher service level.

A successive process of both decisions reduces the possible reachable solutions. This may avoid the optimal solution and can result in a worse solution. Consequently, the usage of simple priority rules and the choice of the material disposition paths after the inspection will not be able to reach a logistical optimum. This potential described above can be outperformed by taking both decisions into account simultaneously in a single optimization algorithm, supported by workload forecasts for a large time horizon.

The next step will be the formalisation of the optimization problem. Because finding the optimal solution will use a lot of computing time, a suitable optimization algorithm has to be chosen. Requirements are an appropriate computing time synchronized with the planning frequency. Hence, trigger points for new optimization runs have to be identified and defined. Finally, the approach will be implemented and tested with data of a regeneration service provider.

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