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Disassembly sequencing in the regeneration of complex capital goods

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Abstract

Despite constantly increasing condition monitoring parallel to operation, maintenance, repair & overhaul (MRO) processes in the regeneration of complex capital goods are still characterised by a high degree of uncertainty regarding the capacity and material demands to be expected from a regeneration order. In order to meet the committed delivery times and dates, the disassembly at the beginning of the regeneration supply chain is of particular importance for the performance of the entire downstream regeneration process. High potential for improving logistical performance lies in an intelligent and logistics-oriented sequencing strategy in disassembly. In addition to technical-physical boundary conditions, the interaction of the disassembly process with downstream process steps and additional other control measures must also be taken into account. The logistical description and evaluation of the sequencing-oriented measures for improving the logistical performance of disassembly in the context of the regeneration of complex capital goods makes their modelling a necessary prerequisite and basis. This paper presents a basic logistical design and modelling approach.

Keywords

Disassembly; MRO; regeneration; complex capital goods; condition monitoring

1. Introduction

Complex capital goods like aircraft engines or wind turbines still show a high monetary residual value at the end of an use phase. The regeneration pursues the aim to keep this residual monetary value through maintenance, repair & overhaul (MRO) measures by transferring the capital goods into a new use phase. [1–3] According to the generic process model of the regeneration the procedure includes the main process steps diagnosis, disassembly, cleaning and inspection, repair, reassembly and quality assurance. [4] The starting point of the regeneration is an input inspection to identify first information that form the planning base for the regeneration process. Despite increasing condition monitoring parallel to operation [5,6] the regeneration is still characterized by a high uncertainty of information regarding the actual damage patterns. [7]. To gain access to single components for a detailed inspection, most of the complex capital goods need to be disassembled. After detailed inspection, reliable information about the repair measures required for regeneration and the spare parts to be procured is available. Once all components are ready for installation, the capital goods are reassembled and quality assurance is completed. While the information blur is constantly decreasing during the regeneration process, there is still almost complete uncertainty about the actual damage pattern during disassembly. [8–10] The increasing availability of data as well as the advancement of algorithms and systems for their analysis and interpretation bear the potential to allow precise statements about the component conditions and thus about the expected capacity loads and material demands due to regeneration even before induction and diagnosis (see Figure 1) [1,11].

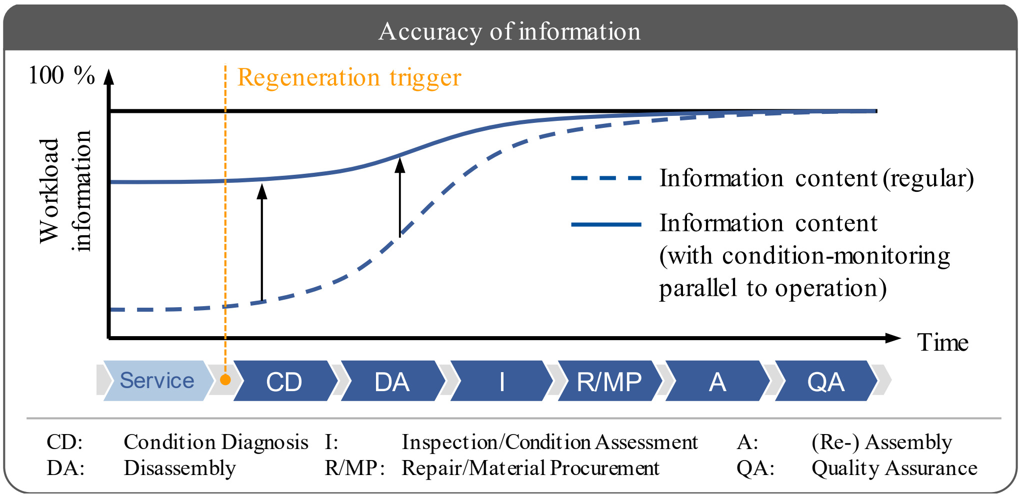

Figure 1: Increasing accuracy of information in the regeneration process (on the basis of [4])

Due to the uncertainty about the exact damage pattern, the depth of disassembly required for the regeneration is rarely known prior to the physical arrival at the regeneration service provider. Consequently, the resulting workload of the regeneration orders and the delivery dates of the disassembled components at the downstream process stages are difficult or impossible to predict and plan. [7] However, in order to comply with agreed delivery times and dates, it is essential to take these interactions into account. [12] In order to achieve a high level of logistics performance despite remaining uncertainty of information, a highly responsive as well as an intelligent supply chain configuration is required. Besides the pooling of particularly time-critical or repair intensive components, especially sequencing and prioritization strategies for disassembly offer the possibility to positively affect the logistics performance of the entire regeneration by reducing the total throughput time of the regeneration TTP_{tot} [13].

2. Boundary conditions for disassembly sequence formation

The flexibility in designing and controlling the disassembly process is limited by a variety of boundary conditions. On the one hand, the freedom in controlling the disassembly process is essentially defined by the order-specific design and selection of the manufacturing principle to be applied. On the other hand, additional processual constraints result from the regeneration process.

2.1 Manufacturing principles for disassembly in the regeneration of complex capital goods

In the regeneration of complex capital goods such as aircraft engines, the construction site principle and the flow principle are primarily used. [14,15] In the case of disassembly according to the construction site principle, the capital goods are positioned at a fixed workplace. From here the disassembled components are transferred directly to the repair workshops or to downstream module and individual parts disassembly workshops. This stationary disassembly is opposed by the application of the flow principle. In this principle, the capital goods are transferred to the subsequent work station after a defined scope of work. The sequence of the work stations to be passed is fixed and either hard or elastically linked via buffering storage. [16] Here, the disassembled components are also transferred to the respective specialized repair workshops or module and component disassembly workshops. In analogy to the application of these manufacturing principles in the manufacturing industry, the application of the flow principle generally offers advantages in terms of efficiency for recurring work, whereas the application of the construction site principle allows more flexible reaction to varying work content. [15,17] Changes of sequences and prioritizations for each manufacturing principle are limited by constructive boundary conditions. When applying the flow principle, the freedom for design is additionally limited to disassembly sequences to be carried out within a work system due to the fixed linkage of the work systems. [14] Thus, comprehensive and extensive manipulations of sequences as well as prioritizations of parts to be disassembled are usually only logistically advantageous if the construction site principle is applied for disassembly.

2.2 Procedural boundary conditions for the disassembly sequence formation

For disassembly sequencing, a process-related special characteristic results from the regeneration process described in the introduction. Assuming a planned disassembly sequence that is initially ordered according to the installation depth of the components (see Figure 2a), the components that are disassembled last correspond to the lowest level of disassembly of the capital good. Under the assumption that reassembly is always performed in a defined, most efficient order with ascending assembly level, the parts must be available in reverse chronological order to the initial disassembly sequence for reassembly after the repair. In the initial state, this results in a "Last Out - First In" sequence across all processes (see Figure 2b). [18]

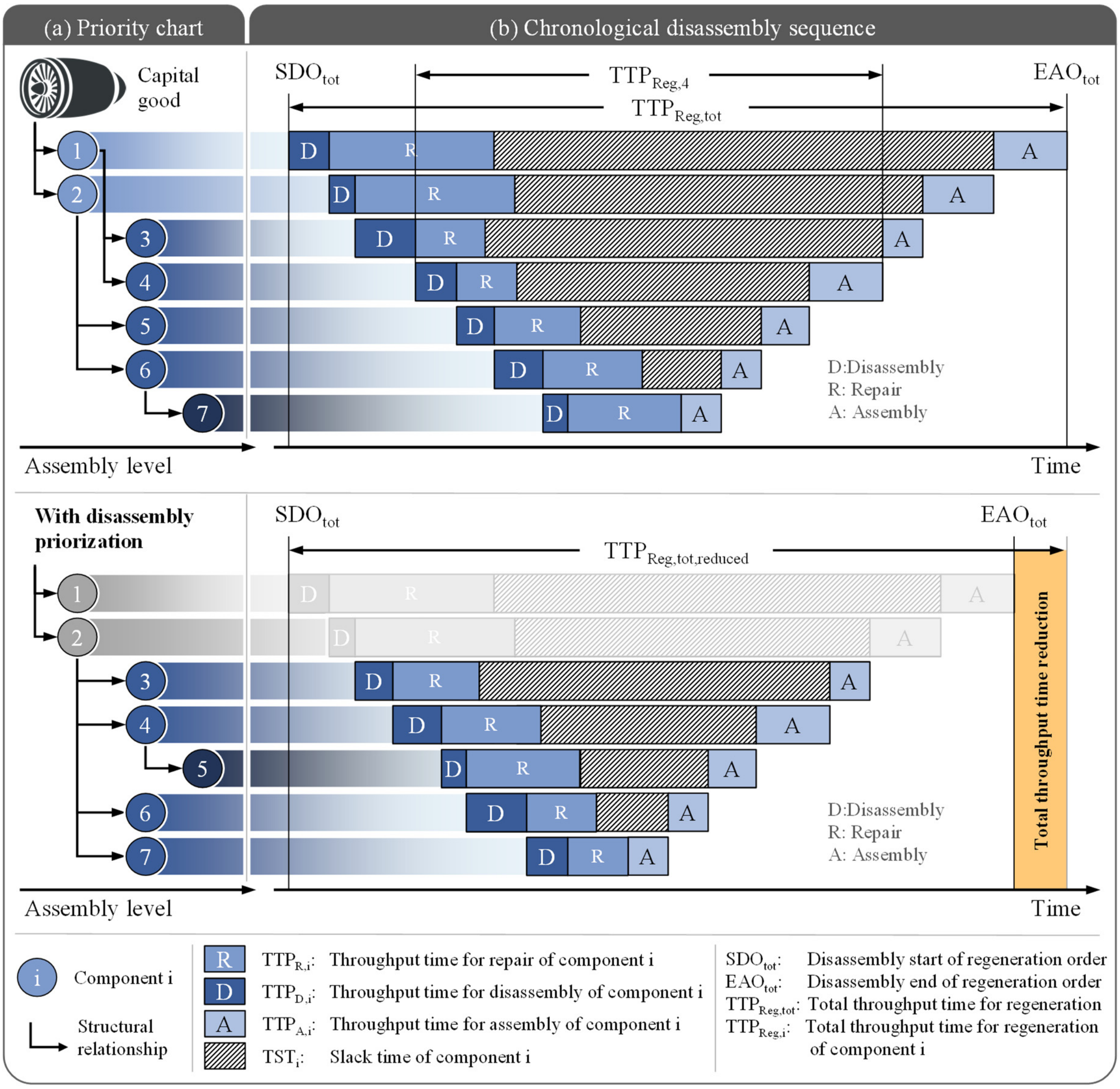

Figure 2: Priority graph (a) and timeline for regeneration (b)

This usually causes long slack times TSTi for the components disassembled first. On the other hand, in particular components disassembled later within the disassembly process must be available for reassembly as early as possible in order to enable further reassembly. Looking at the example of an aero engine these components also are subject to the highest mechanical and thermic loads during operation and thus often require more repair work then components on higher assembly-levels [19].

3. Logistics-oriented disassembly sequencing

When designing an intelligent approach for disassembly sequencing particularly the boundary conditions described before have to be taken into account. The goal is to reduce the overall throughput time of the regeneration order as well as to avoid backlogs due to long repair throughput times that exceed the available repair time between completion of disassembly and the start of reassembly. Therefore components with negative slack times between disassembly and assembly need to be prioritized in disassembly. Under the framework conditions of conventional production processes, Tryzna demonstrated that fast-track orders up to a share of 30% do not compete significantly with each other and thus experience extended lead times themselves [20]. While making these components available to downstream repair processes earlier, it always has to be ensured non prioritized components do not become time critical by these prioritization measures.

The first step is to define the product architecture of the complex capital good to be disassembled and regenerated. In particular, structural or otherwise induced predecessor-successors relations have to be considered. For this purpose, a priority graph can be set up on the basis of work plans for disassembly and reassembly or construction drawings. Figure 2 shows an exemplary priority graph for a regenerative good, consisting of seven components distributed over three assembly levels. The figure shows that, for example, components 3 and 4 can only be disassembled after the component at the higher structural level (component 1) has been disassembled. (see Figure 2a). Starting from a delivery date agreed with the customer, a sequential backward scheduling of the reassembly steps can now be carried out. The planned start and completion dates of the upstream process steps of repair and disassembly are then determined on the basis of the results of the initial inspection. This scheduling can be used to determine the time-based criticality of the components to be disassembled and to make prioritization decisions in favor of the most time-critical components. The interactions with other (sub-) disassembly processes of the same disassembly order or other disassembly orders processed in parallel as well as the competition for limited resources must be taken into account. In order to achieve the highest possible lead time potential in disassembly, prioritizations should be carried out until no further reduction of the regeneration lead time can be achieved by changes in sequence resulting from the prioritizations. This should also include component damage that is only detected during dismantling and therefore requires a greater dismantling depth. Due to this circumstance, the prioritization decisions must be reviewed each time the extent of disassembly is adjusted. If the capacity load of the process elements along the entire regeneration supply chain is significantly changed as a result, a reassessment of the criticality and adjustment of the prioritization decision may become necessary as well. While the primary logistic target pursued through prioritization is a shortening of the regeneration throughput time, the schedule deviation induced by changes in the sequence of disassembly and thus in the availability for the downstream repair must always also be taken into account. If components are accelerated or decelerated during disassembly without coordination with the downstream process steps, there is a risk of a negative influence on the overall logistics performance. If all these framework conditions are taken into account, the logistics-oriented prioritization in disassembly offers the potential for a reduction of the total throughput time of the regeneration order (see Figure 2, bottom).

4. Modelling of logistics processes in disassembly

In order to be able to describe the effects of controlling measures on the logistics performance of the disassembly as well as corresponding interactions with other processes or orders, a proper description and modelling of the processes in the disassembly as well as their interfaces to upstream and downstream processes is required. While the downstream inspection and repair workshops can be modelled as conventional working systems, a logistical description of the disassembly is required. Dombrowski et al. have already developed a disassembly throughput diagram for this purpose. [21] However, this diagram only shows the incoming and outgoing orders in the disassembly process and the subsequent inspection. This allows the description and evaluation of the work in progress (WIP) and load levels in these two process steps. Interactions with the subsequent repair and reassembly processes are not shown. Especially the demand dates of the disassembled components in reassembly and repair as well as the resulting workload in repair are necessary for the logistic description and evaluation of the effects of prioritization measures. In general, different perspectives can be used to describe logistics processes. [16,22] For the description of disassembly processes three perspectives may be used (see Figure 3):

- The order/product perspective,
- the component perspective and
- the resource perspective.

The order perspective considers the individual disassembly order, which consists of various sub-disassembly operations. It focuses on adherence to delivery dates, lead times and individual process costs. The component perspective is used to analyze stocks of individual sub-assemblies, modules and individual parts that flow from various disassembly orders into downstream stocks. In contrast, the resource perspective describes the logistical system behavior of work systems (in this case: disassembly systems). Essentially, the workload and the worklist of the resource as well as the adherence to delivery dates and lead times of all orders in the system during an examination period are analyzed. [22]

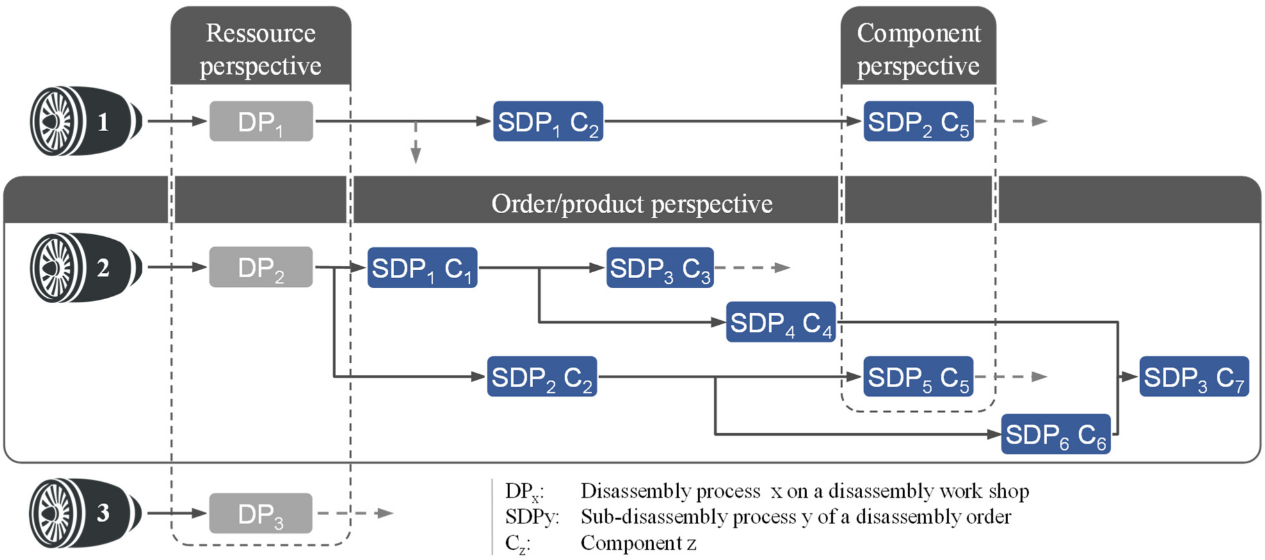

Figure 3: Different perspectives on the disassembly process

In general, disassembly represents a divergence point in regeneration supply chains, regardless of the perspective used. These divergence points have not been made accessible to any logistical description, yet. [23,24]. Depending on the perspective taken, the divergence refers to different subjects. From an order perspective, the divergence lies in the product structure, since the capital good is disassembled into several subordinate assemblies and individual parts. From a resource perspective, divergence in the material flow following the disassembly is considered. The component perspective, due to its focus, is not suitable for describing divergence. The order perspective is therefore used below to describe the order-specific design options in the disassembly process. As logistical description and coupling parameter, the lateness can be used [25–27]. In disassembly, the lateness describes the difference between the actual disassembly completion time EDO_{act} and the originally planned disassembly completion time EDO_{plan} of the overall disassembly order [28,29]. If an order is completed too early ($EDO_{act} < EDO_{plan}$), this results in a negative lateness value. Vice versa a positive lateness occurs, if a disassembly order is completed later than the planned disassembly completion date ($EDO_{act} > EDO_{plan}$). This does not exclusively need to be related to process errors, but may also be the result of backward scheduling from the agreed regeneration completion date EAO_{tot}. Positive lateness can also occur if the disassembly completion date determined by backward scheduling is impossible to realize or is already in the past.

$$L_{out} = EDO_{act} - EDO_{plan} \tag{1}$$

The lateness in the completion of disassembly $L_{D,out,i}$ of a regeneration order basically consist of the lateness in the input of the disassembly system $L_{D,in,i}$ as well as the relative lateness caused by the disassembly process $L_{D,rel,i}$. From an order perspective, the lateness of the disassembly completion of the overall order can also be described as the difference between the actual disassembly throughput time $TTP_{D,act,i}$ and the planned disassembly throughput time $TTP_{D,plan,I}$, based on the input lateness $L_{in,i}$. [30]. In this context, $i \in I$ represent the set of all regeneration orders that are processed on a disassembly work system while $j \in J_i$ do represent the set of sub-disassembly orders within a regeneration order i. Consequently, the lateness of an individual disassembly order can be described as:

$$L_{D,out,i} = L_{D,in,i} + L_{D,rel,i} = L_{D,in,i} + (TTP_{D,act,i} - TTP_{D,plan,i}) \qquad \forall \text{ i} \in \text{I} \tag{2}$$

$$\text{with: } TTP_{D,act,i} = max\big(EDO_{act,i,j}\big) - min(SDO_{act,i,j}) \qquad \forall \text{ j} \in \text{J}_\text{i} \tag{3}$$

Lödding et al. also mathematically described the lateness in the output of a work system as the sum of the backlog-related and sequence-related lateness [31]. This mathematical description of backlog-related and sequence-related components is not directly adaptable to the disassembly process. On the one hand, the statistical independence of the disassembly orders from each other as well as from sub-disassembly orders is not given, because of structural interdependencies between the components. On the other hand, the prioritization of individual components can influence the workload related to the (sub-) disassembly orders, whereby prioritization decisions have a mutual influence on each other as well as on the applied sequencing strategy. Both represent an essentially requirement for the separated, mathematical description of both components [32]. However, the relative lateness can also be attributed to residue-related and sequence-related influencing factors for disassembly. As a result of deviations between the work content assumed for the planning of a disassembly order and the actual workload, there is a backlog. For instance, this can result from component damage that is detected or even caused during the disassembly process and requires a subsequent extension of the disassembly level. A sequence-related lateness results from the prioritization of an entire order $i \in I$ in relation to other regeneration orders as well as the prioritization of individual sub-disassembly orders $j \in J_i$ within a regeneration order. The prioritization of entire disassembly orders can be considered equivalent to sequencing in conventional production processes, since the orders can be assumed to be stochastically independent of each other. Deviations from the generic disassembly sequence by prioritizing sub-disassembly orders within a regeneration order, on the other hand, influence both the lateness of the sub-disassembly orders themselves as well as the actual lead time and thus the output lateness of the overall disassembly and regeneration process. In addition to the direct prioritization of individual sub-disassembly orders, an additional indirect prioritization can result from constructive or other dependencies or links between components under consideration and directly prioritized components. Their effects on the component-specific and regeneration order-specific lateness and lead time must be taken into account when making prioritization decisions as well as the effects on the logistics performance of the entire regeneration system.

5. Conclusion

The increasing availability and quality of status data from the operating phase even before or at the beginning of the regeneration process is opening up more and more possibilities for optimizing the regeneration process. A damage pattern based prioritization of disassembly operations offers the possibility to make heavily damaged components available to the downstream repair processes earlier. This bears potential for shortening throughput times by providing repaired components for reassembly more punctually as well as by shortening the order-specific, critical path. When applying these measures, numerous interactions and influencing factors must be taken into account which cannot yet be described with existing logistic models. Thus, modelling the effects of these measures on the adherence to delivery dates and delivery times of the individual orders as well as on the logistical performance of the regeneration system is an indispensable requirement for a successful application of the measures.

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