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Model-based analysis of reassembly processes within the regeneration of complex capital goods

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Abstract

In regenerating complex capital goods two of the key criteria for success on the market include keeping downtimes to a minimum in order to realize short throughput times and maintaining a high degree of schedule reliability. When unable to comply with the market's demands on their logistical performance, companies that provide regeneration services are faced with significant financial penalties and costs for delays as well as the threat of customers switching to competitors. In addition, regeneration processes must be economically effective. Efficiently designing and planning the entire regeneration process is therefore indispensable.

As a core element, the reassembly at the end of the process chain plays a key role. Since the various material flows merge together here, the logistic quality of the supply processes is particularly visible at this point. Furthermore, reassembly is generally the last value-adding process within the regeneration supply chain. Up until now, descriptive and analytical approaches consider the various supply processes independently of one another and ignore to some degree existing statistical dependencies between these processes. These dependencies however, are frequently found in the industry and have to be taken into consideration when planning tasks and evaluating design measures. This paper will thus introduce the different existing approaches for describing and analyzing reassembly processes and compare them using a case study.

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Keywords: logistic performance measurement; regeneration; reassembly

1. Introduction

Regeneration comprises maintenance, repair and overhaul processes (MRO processes) of complex capital goods. Main objective is a complete restoring of goods. The logistic performance of a regeneration process can ideally be measured and analysed in the reassembly phase [1]. Here, the different material flows merge together and components entering the reassembly have to be coordinated both time and quantity wise [2]. In terms of the reassembly, the most critical logistic objectives are high schedule reliability and low stock levels in the assembly buffers [1]. Strong logistic capabilities with acceptable logistic costs can only be realised in the assembly when supply processes deliver punctually and simultaneously [2]. The logistic performance of processes supplying the reassembly directly impact these requirements. Supply processes that are not aligned result in large waiting stores and insufficient schedule reliability from the perspective of the customer. Since, with the exception of quality assurance processes, reassembly is the last value-adding process before delivering to the customer, the logistic capability here is of particular interest [3]. The products or components in this supply chain process are in a high value creation stage and therefore have a high monetary value. Especially in the area of complex, capital goods, such as jet engines, stationary gas turbines or wind turbines, the logistic

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performance in reassembly is critical. In addition to being highly valuable, complex capital goods consist of multiple components, frequently remain the property of customers and delayed deliveries are tied to strong penalties [4,5].

Generally, the logistic performance of supply chains can be evaluated and assessed using key indicators. Applicable key indicators can be differentiated as pertaining to the logistic performance or to logistic costs. Logistic models are implemented for determining such key indicators and for describing the logistical behaviour of systems. A common model for describing reassembly processes is the so-called supply diagram. This paper will present various approaches for determining supply diagrams and discuss their application restrictions. Furthermore, we will introduce an alternative approach for establishing supply diagrams.

2. Characteristics of Regeneration Processes

Planning the regeneration processes is characterized by several challenges. The regeneration process itself can be divided into different subsystems. In the following section, the specialties of the regeneration process and its different subsystems will be discussed. A focus will be on the so-called convergence points within the supply chain.

2.1. The Regeneration Process

In comparison to a traditional production, the regeneration process is subject to numerous peculiarities. Before reaching the actual value-adding processes, regeneration goods pass through e.g. cleaning, disassembly and diagnosis processes. Further, the work content that has to be managed, can only be realistically estimated after a diagnosis has been conducted [5,6]. However, the diagnosis generally first takes place at the regeneration service provider's site. Capacities such as machinery and personnel though have to already be planned a certain time in advance, before the regeneration good has even arrived. Planning thus generally has to occur while the good that is to be regenerated is still operating and a final diagnosis has not yet been made. The work content can only be planned after the diagnosis of the damaged components is completed and the extent of damage is known. A degree of uncertainty is thus inherent in the early planning that is based on a bill of materials. Whereas in traditional productions, ownership of goods is first transferred to customers after goods have left the production halls, regeneration goods - particularly complex capital goods - remain the property of customers. Customers thus strongly influence which regenerations steps will be taken, for example, or whether new components will be inserted.

The regeneration process can be divided into three subsystems: disassembly/diagnosis, repair and reassembly [4,7]. In practice, subsequent quality assurance processes are planned in, however, these will not be considered in this paper. Besides the value-adding processes, different pools form a basic element in regeneration supply chains. An overview of the process elements involved in regeneration is provided in Figure 1.

Three types of components with different damage statuses are maintained in the storage levels of the regeneration process: (a) New components, that replace components that can no longer be repaired. (b) Components that have already been regenerated by the regeneration service provider or an external supplier. (c) Components that are used and that can still be repaired.

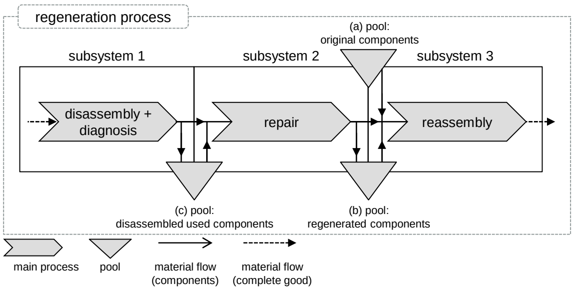

Figure 1: Core elements of the regeneration process (according to [7])

New components as well as those components already regenerated are supplied directly to the reassembly. Regenerated components are integrated when less expensive components are supposed to be used and possibly - when customers permit the use of regenerated components - in order to reduce load peaks in regeneration. The components that are still to be regenerated are first processed in the regeneration subsystem. They then enter either the pool of already regenerated components or reassembly. Integrating already used and worn-out components can reduce load peaks as well as balance under-utilized capacities.

2.2. Description of Convergence Processes

Supply chains in all their various forms can be described by the supply chain's primary processes: storage processes, production processes and convergence processes. Within a regeneration process, reassembly represents a convergence point (Figure 2).

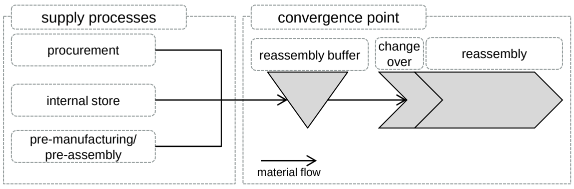

Figure 2: Overview of supply processes and elements in reassembly (according to [8])

Multiple material flows, originating from different sources, meet-up with one another at this point. The components collected by the converging material flows are then processed together over the continuing supply chain. A further example of a convergence point in a supply chain is distribution which, similar to assembly, exhibits the special characteristics of converging material flows. In this case, a number of products are commissioned for a customer order. The order can only be completely compiled after all the products needed for it have entered distribution. Thus, in both reassembly and distribution, components required for an order are gathered in a buffer before further processing.

The reassembly - analogue to a traditional assembly - can therefore be described by a reassembly buffer and an adjacent workstation. The reassembly buffer is fed by the corresponding supply processes. The components entering the reassembly process enter into the buffer before the value-adding reassembly. They are retained in the buffer until all components required for the reassembly job are available; all components waiting for other components thus represent disrupted WIP (work in progress). When transport times between workstations and stores are ignored, the input date of a component into the reassembly buffer corresponds with the output date of the preceding supply process. When a number of complete components sets are available for several reassembly orders, sequencing rules are implemented to help determine the processing sequence. Procurement, in-house manufacturing and internal stores can be defined as supply processes [1]. If supply chains with a number of convergence points are described, a further upstream convergence point such as a pre-assembly is plausible as a supply process.

3. Approaches to Modelling Processes with Converging Material Flows

In the following section, we will introduce common methods for describing convergence points. All approaches aim to describe the logistical system behaviour with the aid of a logistic model and the indicators derived from it. The methods introduced here build on the base model developed by KETTNER [9], which depicts the supply situation with the help of two completion curves.

The area between the two curves yields the disrupted WIP. The disrupted WIP can be seen as a key indicator, which allows conclusions to be drawn about the logistic capabilities of the supply process. Disrupted WIP is created by components not supplied at the same time and thus from supply processes that are inadequately aligned.

3.1. Modelling According to NICKEL

One approach to describing the logistic behaviour of convergence points is the buffer-time-value diagram developed by NICKEL [10]. The buffer results from the temporal difference between a supply order's manufacturing finishing date and the planned assembly start. Considering all of the supply orders together for a reassembly order, results in the disrupted WIP for the observed order. The supply diagram constructed from this, thus depicts the first and last components of a reassembly order, which were not supplied simultaneously. Therefore, the disrupted WIP, evaluated in the supply diagram by the mean monetary value, serves as the basis for the modelling. NICKEL also developed approximation equations for describing input and completion curves. The parameters contained within are empirically determined, making this approach difficult to implement.

3.2. The Assembly Throughput Diagram

According to SCHMIDT the supply diagrams are modelled based on assembly throughput diagrams [8]. In the assembly throughput diagram, the target and actual values of supply orders and the corresponding assembly orders are compared. By cumulatively plotting the inputs of all components over the time, an input curve is created. Similarly, the last component input for an assembly order is also cumulatively plotted. In contrast to NICKEL's approach, the input curve thus reflects all of the components entering the convergence point [11]. The completion curve, in comparison, indicates the last component that enters the convergence point for an assembly order. The resulting supply diagram, consisting of an input and completion curve, allows various indicators (e.g., disrupted WIP or percentage of completed orders) to be directly derived from it. However, in order to establish the assembly throughput diagram, a manifold of operating data is required, which is frequently not readily available in practice.

3.3. The Supply Diagram According to BECK

BECK developed a new method for modelling the supply diagram [1]. Here, the input curve is determined by integrating and summing the individual approximation equations for the output lateness distributions of supply processes. The input curve thus includes all of the components that reach the reassembly buffer via supply processes.

The output lateness distributions required for the modelling according to BECK exhibit different characteristics. The approach is conditional on manufacturing processes implementing FIFO-sequencing (first-in-first-out) so that the output lateness from the prefabrication can be approximated by normal distributions. A storage process can be approximated through an exponential function. Here, it is necessary that store components are supplied on-time or late and *not* before the demand date. Procurement processes can be depicted as a combination of a normal distribution and the store distribution. Whereas, the normal distribution thus reflects the proportion of components produced by suppliers according to the make-to-order principle, the store distribution represents the supplier's make-to-stock proportion (Figure 3).

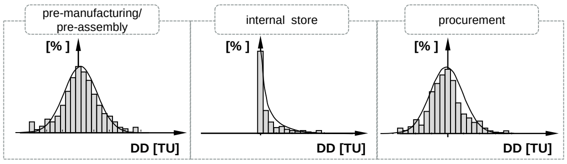

Figure 3: Characteristic output lateness of supply processes (according to [1])

The input curve of the supply diagram is created from the integration of all the approximation functions and their subsequent addition. Thus, for the input probability for a specific lateness (DD):

$$P_{in}(DD) = \frac{f_{in}(DD)}{\sum In} \qquad (1)$$

Whereby f_{in} represents the number of components already supplied with a specific lateness. The sum $\sum In$ is the total number of components that is being assembled during the investigation period.

In this work, Beck derives the completion curve directly from the input curve. The number of components required on average for a reassembly order decisively influences the completion curve. The probability for completion as a function of the lateness can therefore be calculated as:

$$P_{com}(DD) = \left(P_{in}(DD)\right)^{c} \tag{2}$$

Components are considered statistically independent from one another. Accordingly, one component being delayed does not delay the other components required for the reassembly order.

With the aid of these two equations the input and completion probabilities can be derived as a function of the lateness. Furthermore, an approximation equation can be derived for the completion curve:

$$f_{com}(DD) = \sum In \cdot \left(\frac{f_{in}(DD)}{\sum In}\right)^{c_{av}} \tag{3}$$

In order to determine the approximation equation for the completion curve, the approximation equation for the input curve has to be determined first. Moreover, the mean number of components (c_{av}) has to be known.

3.4. The Supply Diagram and its Application Limits

Calculating the completion curve according to Beck is based on the input curve. Due to the mathematical relation between the input and completion probabilities for a lateness class, for every existing input probability greater than zero a corresponding completion probability greater than zero will be calculated.

In comparison, if we consider the storage supply process, whose output lateness is always equal to zero when the modelling assumptions are met, then a completion can only occur when the lateness is greater than zero. In contrast, Beck's approach exhibits a positive completion curve even for a negative lateness class.

The completion curve according to Beck thus already begins in a section in which a completion is in fact not yet possible (see Figure 4).

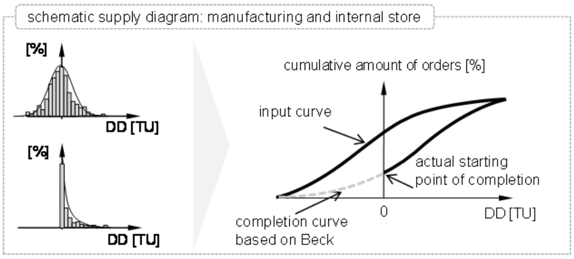

Figure 4: Schematic supply diagram resulting from manufacturing and storage supply processes

Consequently, deviations arise between the calculated disrupted WIP and the actual resulting disrupted WIP. It is thus obvious that the presented approach permits a limited interpretation of the completion situation, especially when there are few intersections between the instances of output lateness. Particularly with output lateness, whose means tend to differ greatly, calculations of the disrupted WIP based on the completion curve according to Equation 2 leads to imprecise outcomes. There are thus two basic application limits:

1.) The completion curve is determined from the input curve, thus the output lateness behaviour of the supply process is not taken into account. The disrupted WIP is incorrectly determined.
2.) The output lateness of the supply processes and thus the components are statistically independent of one another.

4. Alternative Approach to Describing Converging Material Flows

Following, we will introduce an approach, which presents a new basis for calculating the input curve and completion curve. Similar to Beck, the storage, manufacturing and procurement supply processes will continue to be differentiated.

4.1. Method for Calculating the Supply Diagram

An alternative approach to calculating the supply diagram is based on the output lateness of the supply processes. Approximation equations for describing the output lateness are not necessary. This approach resolves application limit 1, outlined above. Whereas Beck derives the completion curve from the input curve, with the new approach both the input and completion curves are modelled based on the output lateness distributions of the supply processes. Furthermore, the individual frequency classes of the output lateness distributions are drawn up directly to determine the supply diagram. This process takes into account the characteristics of the specific output latenesses of all supply processes. It prevents the calculation of a completion probability for every input probability greater than or equal to zero. As long as one of the supply processes does not show an output and therefore an input for the reassembly system a completion is not possible. The disrupted WIP can thus be more precisely calculated with this alternative approach.

The start of the completion curve and therefore the maximum negative completion probability ($DD^{-}_{max,com}$) is directly dependent on the distribution of the supply process' output lateness. Where i describes the number of supply processes, the completion curve begins with a lateness, resulting from the maximum of the maximal negative lateness of all supply processes:

$$DD^{-}_{max,com} = \max\left(DD^{-}_{max,1}, DD^{-}_{max,2}, \dots, DD^{-}_{max,i}\right) \tag{4}$$

To calculate the completion probability ($P_{com}(DD)$) the cumulated output lateness of the supply processes ($P_{cum,i}(DD)$)

has to be accounted for. The number of supply processes continues to be i=1…n. For supply processes, which each provide only one component to the reassembly, the following calculation applies for the completion probability:

$$P_{com}(DD) = \prod_{i=1}^{n} P_{cum,\,i}(DD) \qquad (5)$$

Equation 5 is based on the case where only one component per supply process is required for completion. If, however, more components are needed from one or more supply processes in order to start a reassembly order, Equation 5 needs to be expanded. An example here, would be a manufacturing process that supplies one component for the reassembly, however the store has to punctually deliver two.

In order to account for these circumstances, the output lateness of the supply processes is correspondingly weighted. Accordingly, the output lateness of the store has to be integrated into the calculation through the weighted number of components. The probability of completion as a function of the lateness can be calculated according to Equation 6. The weighting occurs through the number of components per supply process (c_i).

$$P_{com}(DD) = \prod_{i=1}^{n} \left(P_{cum,i}\,(DD)\right)^{c_i} \qquad (6)$$

The weighting factor ensures that the output lateness of supply processes that deliver a number of components to a convergence point is taken into account as a function of the number of components when calculating the completion probability.

4.2. Comparison of different Approaches

A comparison of the supply diagram according to BECK and one calculated with the alternative approach is visible in Figure 5.

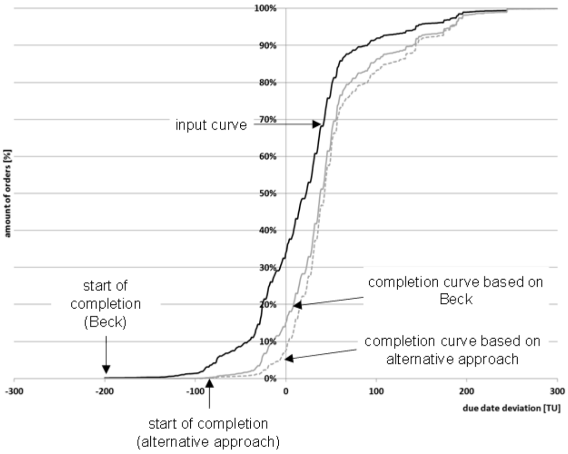

Figure 5: Comparison of completion curves

The diagram shows the supply situation for a company's final assembly step based on feedback data. The company manufactures and assembles complex capital goods in the field of plant construction. The assembly process is supplied by a storage process, a manufacturing process and a procurement process from external suppliers. Further, different amounts of components from each supply process are required in the reassembly for completion. The distribution parameters of the three output lateness distributions are derivable from the feedback data. In this case, an early retrieval from the storage is possible when all other components are already available. This proceeding requires free capacity at the assembly system.

In particular, the exhibited difference in the disrupted WIP demonstrates that the alternative approach results in a significantly greater value (deviation of +29,9% compared to BECK). By including a monetary evaluation of the WIP, the disrupted WIP becomes more relevant: 29,9% more disrupted WIP, ties up 29,9% more capital. The deviation can be explained by the difference in the means of the distributions. With the alternative approach, the completion curve starts as soon as all supply processes show a first output. Thus the completion curve has another starting point than the one according to BECK. This is why a larger disrupted WIP is indicated.

If different output distributions of the supply processes are considered, it becomes clear that, especially with supply processes whose means strongly differ and which have a similar variance, there are considerable differences between the approaches' characterization of the disrupted WIP. With decreasing overlap between the instances of output lateness and thus different maximum negative latenesses, the lateness span increases in which no completions can result due to a lack of components from a supply process.

BECK however indicates a completion probability during these time spans. In the following, two supply processes should be considered. They both show the characteristics of manufacturing processes. Their lateness output distributions can be described by the same standard deviation (SD=3) but different mean values. Further, one component from each supply process is necessary for a completion (c=1). If the two manufacturing processes are displaced in relation to one another, it becomes visible that with growing delta of the means, the error in the disrupted WIP increases as well (Figure 6).

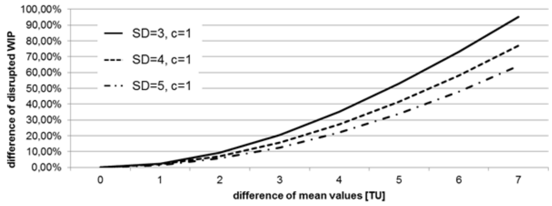

Figure 6: Error development of the disrupted WIP depending on the mean difference

Further, both distributions are given a greater standard deviation (SD=4 and SD=5). The deviation of the disrupted WIP correlates with the difference in the mean. The further apart the means are, the greater the lateness span in which no completion is possible, despite first inputs.

The occurring difference thus has to be determined case-by-case. The error progression is also influenced by the standard deviation of the individual distributions and the number of components per workstation, required for the subsequent process step.

4.3. Accounting for Dependencies between Supply Processes

The preceding discussion is based on the assumption that there are no dependencies between the supply processes in terms of the output lateness.

However, in practice, is it plausible that when there is a delay in one process, other processes will be consciously delayed, or that other processes will be early when a supply process receives its provision early. This is clarified using the example of storage as the supply process. Provided that the required components are already stored for a period before the demand date, with an early provision from manufacturing, it is also possible for components to be removed early from the store (Figure 7). Consequently, the output lateness of the store does not begin with lateness DD = 0 TU.

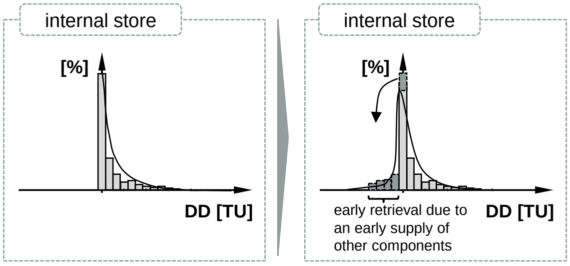

Figure 7: Impact of early provisions on store output lateness

The described alternative approach allows such a shift to be accounted for in determining the completion curve as well. Since the frequency classes of the output lateness are drawn upon directly, changes in the form of the distribution can also flow into generating the supply diagram.

Similar dependencies are also possible between production processes and procurement processes. Assuming dependencies between supply processes leads to improved supply situations. Although components might be supplied early or late, they arrive at the same time due to the dependencies. Input and completion curves are thus closer to one another. It is obvious that by taking the dependencies into account the disrupted WIP is minimized. An approach to considering the statistical dependencies between components in the completion is provided by Hund. Hund reduces the number of components which can be considered for the supply situation to only the independent ones [12].

If in determining the output lateness of the supply process, historical feedback data are drawn upon, these reflect the dependencies - given that the feedback data reflects the actual behaviour.

5. Conclusion

Within a supply chain convergence points represent a fundamental core process. The logistic capabilities of all preceding supply processes are reflected here. In order to attain a high degree of due date compliance and minimize disrupted WIP, the goal should be to ensure all components needed for a subsequent order arrive at a convergence point punctually and at the same time. In terms of regeneration processes for complex capital goods, the reassembly represents a convergence point. Since it is the last value-adding process before delivering to the customer and products at this value-adding stage are highly valuable, logistic objectives have to be attained at this point in the supply chain. On a design and planning level, a model based description of the convergence point is thus indispensable for meeting this target positioning. Existing modelling approaches exhibit limitations with regards to universal applicability. With the aid of the new approach introduced here for calculating completion curves, the previous application limits can be resolved. The disrupted WIP can therefore be predicted more precisely. Comparing the different instances of output lateness for supply processes demonstrates that with the help of this approach the correct disrupted WIP can be indicated also for distributions with strongly deviated means.

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