SPARE PART MANAGEMENT WITHIN PRODUCT REGENERATION

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Abstract—Generally, product usage goes hand in hand with wear that varies depending on operating conditions. In particular, goods that still have a high monetary value at the end of their lifecycle can be repaired and returned to their original functionality. Production regeneration is responsible for this restoration and includes the maintenance, repair and overhaul tasks for processing used goods. Regeneration focuses primarily on complex investment goods. Businesses that provide these services apply manufacturing methods to restore the functionality of individual components before reassembling them in a final value-adding step. In order to attain a high logistic performance, it is sometimes necessary to supply spare parts from a warehouse instead of conducting laborious repairs. A warehouse can then store already regenerated components and supply them on demand. This paper presents a method for logistically describing these so-called internal pools, which can be used by regeneration service providers when designing their internal supply chain and directly influences their attainable logistic performance.

Keywords—regeneration, spare part management, logistics efficiency, missing part situation

I. INTRODUCTION

Regeneration refers to all of the tasks required to repair complex investment goods such as motors of rail vehicles, stationary gas turbines, aircraft engines and wind turbines [1]. At the end of their service life, the products functionality is reduced due to damages caused by wear or external conditions. It is therefore imperative to restore them in order to ensure their further economic use. This occurs at so-called regeneration service providers, which are frequently organized according to the workshop principle [2].

Regeneration service providers are faced with the challenge of punctually processing orders and making them available for customers. Delayed completions, particularly with complex goods, result in extremely high lateness penalties and may cause clients to move to competitors. These penalty fees are often contractually negotiated at the start. High schedule reliability can thus be considered the most important logistic objective. In particular, the primary focus is the related due date compliance. Since goods generally remain the clients property, completing regeneration orders early is not tied to inventories that impact profits. However, delivering an aircraft engine late, for example, can mean in a worst case scenario that the customers plane remains grounded. Figure 1 provides an overview of the existing logistical targets that regeneration service providers face in order to realize highly efficient logistics [3].
In order to punctually complete a regeneration order, it is essential that all of the components required for reassembling a good before it is shipped back to the customer, are already available in the reassembly at the start of this final value adding step.

II. ORGANIZATION AND EVALUATION OF THE REGENERATION PROCESS

Generally, the regeneration supply chain is divided into the processes: disassembly/inspection, repair and reassembly [4].

Whereas, the good being regenerated is taken apart to a predefined degree during the disassembly, the inspection determines the final diagnosis for each of the resulting components. Once the inspection is completed, the exact work content of the components is known and components can be sorted into the following categories:

- serviceable
- repairable
- scrap

All components thus enter the reassembly buffer via different supply processes depending on their damages. The reassembly buffer is located before the value-adding reassembly and serves as the collecting point for incoming components. Only once all of the components required to complete an order are present, does it enter the final step of the supply chain. The key significance of the reassembly, in which all the supply processes converge, is depicted in Figure 2. In order for the reassembly process to start on-time, it is necessary that all required components have also entered the buffer punctually. When this is not the case, individual components have to wait for the completion of the order. This results in a missing part situation in the reassembly, also referred to as disrupted WIP. Missing parts thus cause stock to build-up in the buffer and delayed inputs lead to late reassembly starts. A high level of disrupted WIP is therefore an indicator that supply processes are not properly aligned.

Figure 1: Logistical Targets for Regeneration Processes (acc. to [3])

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Figure 2: Schematic Structure of a Regeneration Supply Chain (acc. to [4])
however weighted with the value of the complete order. The input and completion curves thus end at the same point [5]. A schematic supply diagram can be seen in Figure 3.

The lateness distributions of the supply processes are of primary importance in determining the supply diagram. Based on them both the input and completion curves are calculated. The input probability per lateness class depends on the cumulated probability of each supply process ($P_{\text{cum}}$). It thus comprises all components that enter the reassembly buffer. Therefore, the following equation results for the input probability $P_{\text{in}}(DD)$ [5]:

$$P_{\text{in}}(DD) = \sum_{i=1}^{n} (P_{\text{cum},i}(DD))$$

The completion curve only contains components that are responsible for the completion of a reassembly order. To calculate the completion curve when a number of supply processes are involved, the number of components supplied from the respective supply processes on average for each of the reassembly orders also has to be taken into account ($N_{c.i}$). Given that all supply processes provide components, the equation for the completion probability $P_{\text{com}}(DD)$ is [8]:

$$P_{\text{com}}(DD) = \prod_{i=1}^{n} (P_{\text{cum},i}(DD))^{N_{c.i}}$$

In order to indicate the monetary value of the disrupted WIP, calculations can be made with weighted lateness distributions. Orders are then weighted with their values, so that the supply diagram ordinate is in €. The disrupted WIP is then calculated by subtracting the two areas found below the input and completion curves. Furthermore, the value of the disrupted WIP can be determined for specific classes. To calculate the mean disrupted WIP, the total disrupted WIP is divided by the observation period [5]. Lower disrupted WIP levels indicate supply processes are aligned well with each other, since few components have to wait for other components to complete the order [9]. However, this does not inevitably mean that the supply is on-time. To determine this, the lateness distribution of the completion curve has to be generated, and from there the mean and standard deviation of the distribution can be derived. Correspondingly, both the disrupted WIP as well as the completion lateness has to be taken into account when evaluating the missing part situation.

III. POOLING SPARE PARTS

For regeneration service providers, one design option is to include a regeneration pool. In the pool stages, components that have already been restored either internally or “out-of-house” are stocked. These components are assigned to a specific order on an as-needed basis. They are generally stored without being allocated to a fixed order.

In addition to selecting which components to stock in the pool, one of the key factors to consider when designing the pool is the replenishment strategy. These are defined by the order quantity, target stock, reorder and order intervals. Strategies can be divided into methods according to their order rhythm or order point. The following basic types of replenishment can generally be identified [10]:

- $s,q$-strategy: variable order interval, fixed order quantity
- $s,S$-strategy: variable order interval, variable order quantity
- $t,q$-strategy: fixed order interval, fixed order quantity
- $t,S$-strategy: fixed order interval, variable order quantity

Since the regeneration process is subject to uncertain information, the suitability of these strategies varies. Using a utility analysis though, we can compare the
strategies. A utility analysis generally serves as a systematic preparation for decision making (according to [11]) and is comprised of five steps.

Setting the Analysis Criteria
Criteria for the analysis are selected in view of the regeneration’s logistic objectives and the business environment in which the regeneration service provider works in. Since regeneration takes place in a dynamic environment, it is critical that the warehousing strategy allows current inventory levels to be quickly monitored and the pool to be reactive to demand fluctuations. At the same time, since components being regenerated are very capital-intensive, low stock levels need to be attained because, although components being repaired remain the property of the owner, pool components are owned by the regeneration service providers. To take into consideration capacities, the stock area needs to be kept to a minimum. This criteria correlates with the previous. Finally, the effort required to implement or apply the warehousing strategy is evaluated in order to assess the economic efficiency of managing the component pool.

Evaluating the Individual Criteria
Afterwards, all of the analysis criteria for the different warehousing strategies are evaluated based on the degree they are fulfilled. A scale consisting of five degrees of fulfillment, ranging from ‘minimally fulfilled’ to ‘highly fulfilled’, is used for this. The resulting number of points with regard to the degree of fulfillment are then weighted with the criterions percentage. This procedure is repeated for all of the criteria and for all four warehousing strategies.

Deriving the Overall Utility
The overall utility of a warehousing strategy is calculated by adding the individual weighted target fulfilment degrees of every single criteria.

Comparison
Comparing the results indicates that the warehousing strategies with variable order intervals demonstrate a high overall utility or suitability for regeneration (see figure 5). This superiority is primarily due to the fact that the s,S- and s,q-strategies make it possible to replenish pool stock much more flexibly. The field of regeneration is characterized by stochastic demands, thus the criterion „reactive to demand fluctuations” impacts the analysis the most.
directly supplied to reassembly. The pool stage considered here was located between the repair and reassembly shops, and supplied the reassembly with pool components on demand. Only components that are time critical for a regeneration order and are available are pooled. The reassembly buffer forms the convergence point. Once an order is complete, it releases the corresponding components for the final reassembly. Damages and thus the allocation of processing times and material flows were randomly designated. The analysis of the simulation studies provides key indicators of the logistic performance at the process chains convergence point. Included among these are the mean lateness of all supply processes as well as the resulting supply situation in the reassembly buffer. With the aid of the supply diagram, corresponding figures regarding the lateness (here: mean and standard deviation) and disrupted WIP as well as the degree of completion at the demand date were calculated. In contrast to [12] it was assumed that by pooling certain components, the lateness in the repair section does not change. With that assumption we are addressing long-term planning tasks of regeneration service providers. The results of a simulation study are shown in figure 6. In order to compare the strategies we made sure that the same amount of components enters the pool during the simulation time.

<table>
<thead>
<tr>
<th>Warehousing strategy</th>
<th>Resulting disrupted</th>
<th>Realized pooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>s,q-strategy</td>
<td>8.049 €-SCD</td>
<td>17</td>
</tr>
<tr>
<td>s,S-strategy</td>
<td>8.049 €-SCD</td>
<td>17</td>
</tr>
<tr>
<td>t,q-strategy</td>
<td>8.146 €-SCD</td>
<td>11</td>
</tr>
<tr>
<td>t,S-strategy</td>
<td>8.057 €-SCD</td>
<td>15</td>
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Figure 6: Simulation Results

The results of the simulation study demonstrate that both the s,S-strategy and the s,q-strategy (which can be considered dynamic policies) attain better results than the other strategies. The simulation study therefore confirms the results of the utility analysis previously conducted. It is obvious that the pools have to be replenished with spare parts using the most flexible parameters in order to realize as many pooling events as possible.

V. INFLUENCE OF SPARE PART POOLING ON LOGISTIC OBJECTIVES

We will now describe the influence of pooling on the logistic objectives, given that only components that are on the time-critical path are supplied from the pool for individual orders. Obviously, pursuing this strategy can shorten throughput times for the repair of affected orders. This also influences the delivery time from the customers’ perspective. As long as the reassembly has corresponding capacities available, early completions also make earlier deliveries possible. Moreover, when the component that is on the critical path for the throughput time and thus responsible for delayed completions is supplied from the pool, the positive lateness of the order in consideration, can be reduced and with that the schedule adherence be improved.

Supplying a component from the pool, means that one less component, which otherwise would enter the convergence point late, has to be processed in the repair shop for the considered order. The maximum lateness of that regeneration order is thus reduced. With that, the disrupted WIP occurring at the reassembly buffer can also be reduced.

Through the pools stock level, regeneration service providers have the possibility to supply as many parts as possible via the pool, rather than through the repair shop. Nevertheless, the logistic costs that arise through the capital tied up in the pool stock have to be taken into account. With increasing pool stock, logistic costs climb. The level of the total pool inventory is influenced by the different components suitable for pooling as well as their individual stock structure. Since regenerating complex investment goods entails capital intensive components, the tied up capital and other storage costs are decisive objectives.

The components that can be replaced by a pool component are also restored using internal resources – though this can happen at a later time – the pooling therefore does not have any direct influence on the load and therefore the capacity utilization in the repair shop. Figure 7 provides an overview of the qualitative development of the logistic objectives with increasing pool stock.
FURTHER DESIGN OPTIONS FOR ATTAINING STRONGER LOGISTIC PERFORMANCE

The described simulation model was also used to analyse typical sequencing rules within the frame of regeneration. The following sequencing rules were investigated:

- shortest operating time
- longest operating time
- FIFO
- earliest planned due date
- least slack

The simulation study of the sequencing rules was initially conducted without implementing pooling components. The decisive parameter was determined to be lateness. The results indicated that the sequencing rules oriented on the work content (shortest operation time, longest operation time) lead to significantly greater lateness than other sequencing rules. This can be explained in that the processing times of an order’s individual components will vary depending on their damage and there are thus numerous sequencing interchanges. This in turn causes considerable missing part situations in the reassembly buffer, since the components that can be quickly and easily processed enter the buffer first. The components requiring more extensive processing times only manage to enter the material buffer after considerable delay. In contrast, no sequencing interchanges occur with the FIFO rule. One of the key advantages of the FIFO rule is how easily it is applied, whereas with the least slack rule, the next priority has to be re-evaluated after each processing step. Nevertheless the least-slack-rule also results in much fewer lateness than the work oriented rules.

With the results of the sequencing rules simulation study, it is obvious that a due date oriented sequencing rule is best suited for attaining the regeneration specific logistic objectives. These sequencing rules combined with pooling components provide powerful control levers for regeneration service providers to influence both their logistic performance and logistic costs.

VII. CONCLUSION

The results of the simulation studies show that within the frame of regeneration, applying dynamic replenishment strategies and due date oriented sequencing rules provide support in attaining logistic targets. Due date compliance is paramount when regenerating complex investment goods. The aim here is to achieve a high degree of due date compliance from the perspective of the end customer. This requires all necessary components to be supplied to the reassembly shop punctually. The reassembly is therefore the supply chains central convergence point, in which the logistic performance of the supply processes are assessed and in which the impact of the pool design as well as the impact of the sequencing rules is reflected in missing part situations. In particular, pooling provides a key control lever for improving the logistic performance. However, the increasing logistic costs, in the form of climbing inventory and process costs, have to be considered. Combined with due date oriented sequencing rules, the timeliness of supplying components at the convergence point of the regeneration’s supply chain can be continually and positively influenced. Furthermore, it is evident that dynamic replenishment strategies are particularly well suited for a strong logistic performance in regeneration processes. Even when there are further supply processes in the industry such as direct procurement, regeneration service providers do not generally have much room for negotiation with them, since, for example, replenishment times are externally set due to geographic circumstances. Pools and sequencing rules therefore represent the most important control levers that regeneration service providers can influence.

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