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Regeneration Supply Chain Model and Pool Stock Dimensioning

Tammo Heuer[1], Benedict Wildmann[1], Torben Lucht[1], Peter Nyhuis[1]
[1]*Institute of Production Systems and Logistics (IFA), Leibniz University Hannover, Germany*

Abstract

When regenerating complex capital goods, on-time delivery as the most valuable customers' requirement is crucial. Schedule reliability and throughput times are being trimmed to meet their targets as precisely as possible while keeping the logistic costs in-check. After disassembly, a significant number of components face relatively long repair times and need to be reassembled on a timed schedule. The configuration of internal supply chains offers the potential to improve schedule reliability. Pooling strategies are developed and discussed to achieve higher flexibility and positive effects on logistical performance. Pools help with reducing throughput times and short-term capacity allocation to satisfy an optimal on-time schedule. Serviceable (SA) components that have already been repaired, are stored in SA-pools and, if necessary, are allocated to the reassembly. The focus of this paper is the non-serviceable pool (nSA-pool), which provides repairable components to the repair stage. The nSA-pool helps to streamline the workflow before components reach several repair shops and has a direct impact on the repair process. Therefore, a model that allows the comprehension of interactions within the internal supply chain was developed and expedient pooling strategies were derived. Furthermore, the related pool stock dimensioning of preceding pools (nSA) before the repair stage and following pools (SA) are put into perspective.

Keywords

Complex capital good; regeneration supply chain model; pool stock dimensioning

1. Logistical issues in regeneration supply chains

Complex capital goods are characterized by a high number of components and high investment costs [1]. Examples are aircraft turbines, machine tools, rail vehicles, transformers, wind turbines and aircraft. The regeneration of complex capital goods has gained importance in many industries due to their high value and associated high downtime costs. Thus, after a usage cycle, the regeneration process has the objective to regenerate the used equipment. Regeneration includes the comprehensive preparation of the complex capital goods to its original delivery condition and may go further than maintenance improving its functionality [2]. Due to the high investment value of capital goods, long throughput times and delivery delays are not acceptable [3]. Quick and predictable re-use of complex capital goods is necessary. In addition to high delivery reliability and short throughput times, logistics costs must be kept low [4]. Therefore, stable regeneration processes are becoming a factor of success in the competition [5,6].

The time-consuming repair is confronted with uncertain capacity requirements, as damage to components of the complex capital goods can rarely be predicted [7]. Internal pooling stations are added to the regeneration supply chain to ensure flexibility and high delivery performance. They are a proven instrument for making short-term adjustments in the event of under- or over-utilization of repair capacities and help improve the on-time supply of components. [8,9] This paper discusses two variants of pooling solutions. Both try to improve the logistical performance of the preceding and following stages in the regeneration supply chain. The serviceable (SA) pool stores repaired components only. It is situated post-repair in the regeneration process. Contrary to that, the non-serviceable (nSA) pool temporarily stores damaged components coming out of disassembly. In order to make logistic problems within the internal regeneration supply chain transparent, connections between stages of the regeneration path need to be made visible. This paper also integrates the proposed pooling capabilities to develop an overview. Due to volatile order volumes and problematic utilization planning, pooling strategies require a sophisticated pool dimensioning approach to ensure high logistical efficiency, which is characterized by a high ratio of logistical performance and logistics costs [8,10].

2. State of the art of regeneration supply chains

Configuration of the regeneration supply chain plays a vital role within the regeneration process of complex capital goods [11]. This chapter allows an overview of the regeneration process and clarifies how the internal supply chain works with different pooling configurations. The regeneration process is visualized in Figure 1. The regeneration process of the service provider is marked in anthracite and can be separated into five main stages: disassembly, inspection, repair, reassembly and quality control [8]. When specific indicators are met, the regeneration process is triggered. For instance, regeneration triggers can be sudden damage or legal requirements, such as regeneration after a certain period of use [12]. Even before shipment and disassembly, the regeneration service provider estimates a probable throughput time. The following disassembly is the first physical contact of the complex capital good with the regeneration service provider. The complex capital good is getting disassembled into its subassemblies and components. For a more precise analysis, the following inspection is essential. The inspections findings enable precise planning of the work scope of all following work stations [7,13].

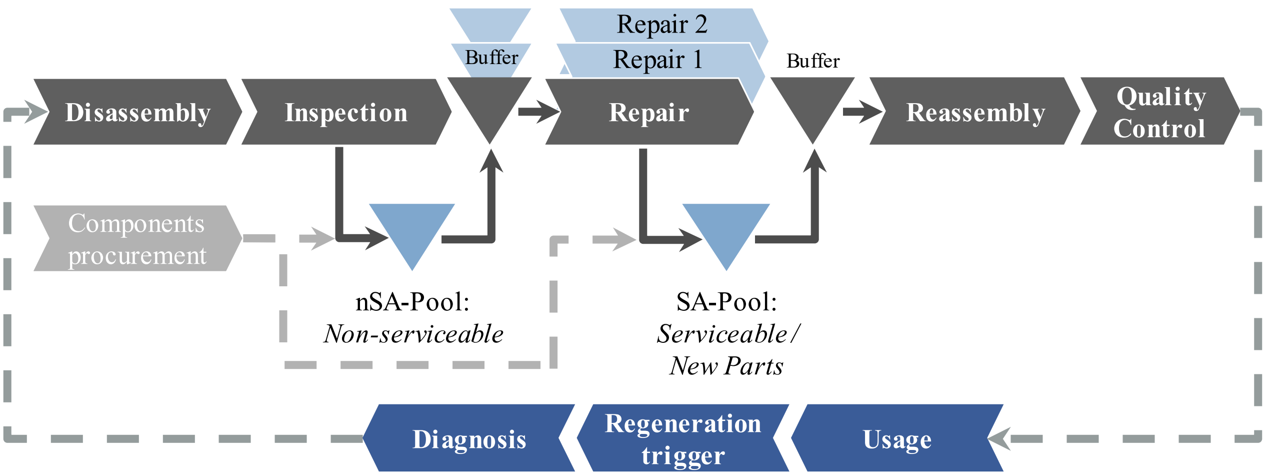

Figure 1: Regeneration supply chain [9]

Optionally, the nSA-pool could be placed in between inspection and repair. If components do not need to be repaired and provided to reassembly immediately, they get stored in the nSA-pool. Otherwise, the components are forwarded to a repair stage. Here a high share of the throughput time is being used. The variability of the different components leads to a substantive difference in resulting repair times [1]. In order to meet the tight schedule for reassembly, all components must arrive on time [13]. Differences in arrival time are mainly influenced and rooted in the repair process [14]. After repair, single components are converging in a buffer uncoupling previous processes and reassembly. Between repair and reassembly, the SA-pool is located. Repaired components get stored in the SA-pool until they are needed for reassembly. Thus, the SA-pool allows on-time delivery by providing the required components to reassembly. Furthermore, new components can be procured externally to converge in reassembly. In other instances, components must be replaced by new components because they are not reusable or because the particular component has been irreparably destroyed during its usage cycle. However, ordering new components is often associated with costs and other difficulties and does not fit the maintenance providers intend [15]. Components for both the nSA- and SA-pool can be procured externally. After the successful convergence of component streams and accomplished reassembly, the final test and quality control make the complex capital good ready for shipment to the customer. Subsequently, another usage cycle starts and after a defined amount of usage time, a new regeneration process should be started. [16] Following, the two pools and their interactions within the internal supply chain will be described with a more detailed look.

2.1 No integrated pooling

A regeneration supply chain without SA- and nSA-pooling has a simple structure. It is advantageous that no nSA- and SA-stocks need to be maintained. As a result, less storage and logistics space is required, and management of the pools is not needed. Restructuring processes to adapt to a pooling solution in the regeneration business can be an extensive project for a regeneration company. With no pooling, the procurement of new components is required for every replacement of scrap components [17]. However, the costs of the regeneration process are increased when purchasing new components. Therefore, it has to be determined whether a new component procurement is carried out only for scrap components. If there are any problems with the repair time of components, deadline shifts, and maybe penalty costs have to be accepted. Hence, without pooling, flexibility to react to problems within the repair is limited [7]. With no integrated pooling configurations, there tends to be a high amount of work in progress (WIP) taking up space in workstations of the repair and tying up capital. Due to e.g. problems in the repair, components can be overdue for reassembly. This results in a disrupted WIP in the reassembly, which contains all components that have to wait for delayed components to get reassembled to the complex capital good. Especially the SA-pool can reduce this issue. [8] But also, the use of an nSA-pool enables a purposeful work in the repair and, further, allows a suitable delivery of components and thus less disrupted WIP in reassembly. Additionally, it is difficult to compensate for utilization fluctuations without pooling. Hence, the repair must be accurately timed and scheduled in order to uphold punctuality of the entire regeneration supply chain. [14]

2.2 SA-pool

Implementation of an SA-pool has been discussed by other authors before. Often they are focusing on regeneration processes of aircraft components [18]. Another focus area that differs from considerations in this paper is the discussion about external pooling solutions that do not emphasize the direct repair process itself [19]. Instead, external pooling comprises the storage of spare components in a central warehouse to which several companies have access to and which considers the regeneration supply chain at a network level. FRITZSCHE investigates material availability of aircraft components with dynamic failure rate for external pooling, which makes pool dimensioning more precise and reduces storage costs for the network [19]. The original model used for this purpose is based on the Metric for Recoverable Item-Control (METRIC) model developed by SHERBROOKE [20]. The METRIC model and its numerous extensions concentrate on external pooling sectors and cross-company multi-level regeneration supply chains, where the single regeneration service provider cannot adapt the external pooling to its specific requirements. Thus, this paper focuses on a universal implementation of the SA-pool to the internal regeneration supply chain.

Based on the positioning before repair, the SA-pool primarily serves the timely provision of components in order to complete customer-specific orders on time. With the extension of the system by an SA-pool, increased on-time delivery to reassembly and thus an improved missing parts situation in reassembly can be expected [9]. This improvement reduces the costs for previous and subsequent stations of the SA-pool by offsetting costs for maintaining an SA-pool. The improved missing parts situation is caused by the fact that the SA-pool synchronizes the completion of individual orders at the convergence point and consequently reduces disrupted WIP. Additionally, the SA-pool can generate a job-specific safety time by bringing forward requirement dates. [8,10] The repair achieves an improvement of flexibility. Preparatory repairs and existing material capacity in the SA-pool prior to reassembly means that the repair does not have to focus on providing components for reassembly only. Instead, components that are not currently needed can be repaired, pooled in the SA-pool, and added to the process later to ensure long-term availability of predicted component demands and leveling the repair workload.

Various strategic objectives are required for spare components pooling. Depending on the pursued strategy, different targets for regeneration logistics are primarily influenced. KUPRAT differentiates five different pooling strategies: [8]

1. The timely improvement of the already-existing situation in reassembly that positively influences punctuality and a positive due date deviation.
2. The reduction of regeneration costs and manufacturing costs.
3. Reducing or leveling the repair throughput time focusing on the throughput time.
4. Utilization-oriented deployment of pool components focusing on utilization.
5. Residue-oriented deployment of pool components which try to improve punctuality.

The focal point of the SA-pool is to support punctuality and on-time completion in the reassembly process. The combination of strategies 1 and 3 is the most accommodating way for an SA-pooling strategy. This can be described as a "reassembly-oriented pooling strategy" [8]. A major problem of supply chain configurations without pooling solutions described above is that in situations where a component is missing for reassembly, only the procurement of new components is an option [21]. Here the SA-pool offers a simpler and cheaper possibility. The decision of whether to take a new component or an SA component requires definitions and individual decisions. Even with SA-pooling, workload fluctuations in the repair are still to be expected [8]. For the SA-pool, a stock of components has to be defined. This stock takes up area and logistic capacities as a separate entity in the overall logistics planning. Due to more complex material flow, logistics planning becomes more extensive, and the picking effort increases, but with an SA-pool, the logistical performance for the customer can be significantly increased, and on-time delivery is ensured.

2.3 nSA-pool

The focus of research so far has largely been on the SA-pool; here, the additional nSA-pool is discussed. With only an SA-pool, since the repair only has a certain capacity, components from the disassembly must be stored in a buffer of the repair stage [8]. In order to gain a central distribution point and further confront logistic issues in front of the repair, an nSA-pool is added to the model. Then, components requiring repair are managed centrally by the nSA-pool. Therefore, there is a lower WIP in the repair. [10] The nSA-pool aims to achieve a balanced capacity utilization in the repair. The nSA-pool can enhance the utilization in repair by releasing nSA-components for repair when the current workload in the repair is low. A well utilized repair also results in a balanced load in reassembly and, thus, in conjunction with the SA-pool, increases schedule reliability and on-time delivery. Considering the descriptions mentioned above of pooling strategies for the SA-pool, the nSA-pool's focus is on the utilization in the repair stage. The most suitable strategy is strategy 4, as mentioned in chapter 2.3. As a result, the nSA-pool strives for a "utilization-oriented strategy", especially for the repair stage. Due to central importance for the regeneration processes and the great expenditure of time in the repair, streamlining the logistic processes in or before repair also has a significant effect on the other stages. Compared to the models described above, the combination of both pool stages has the highest logistical space requirement. Hence, logistics control is becoming more complex. However, capacity utilization and logistical performance can be improved considerably.

3. Pool Interactions

Hereafter, interactions of the pools and effects on logistic parameters are described and summarized in an interaction model depicted in Figure 2. Since the focus of this paper is on the management of single components, interactions and logistic parameters between disassembly as the divergence point of the complex capital good and reassembly as convergence point are considered.

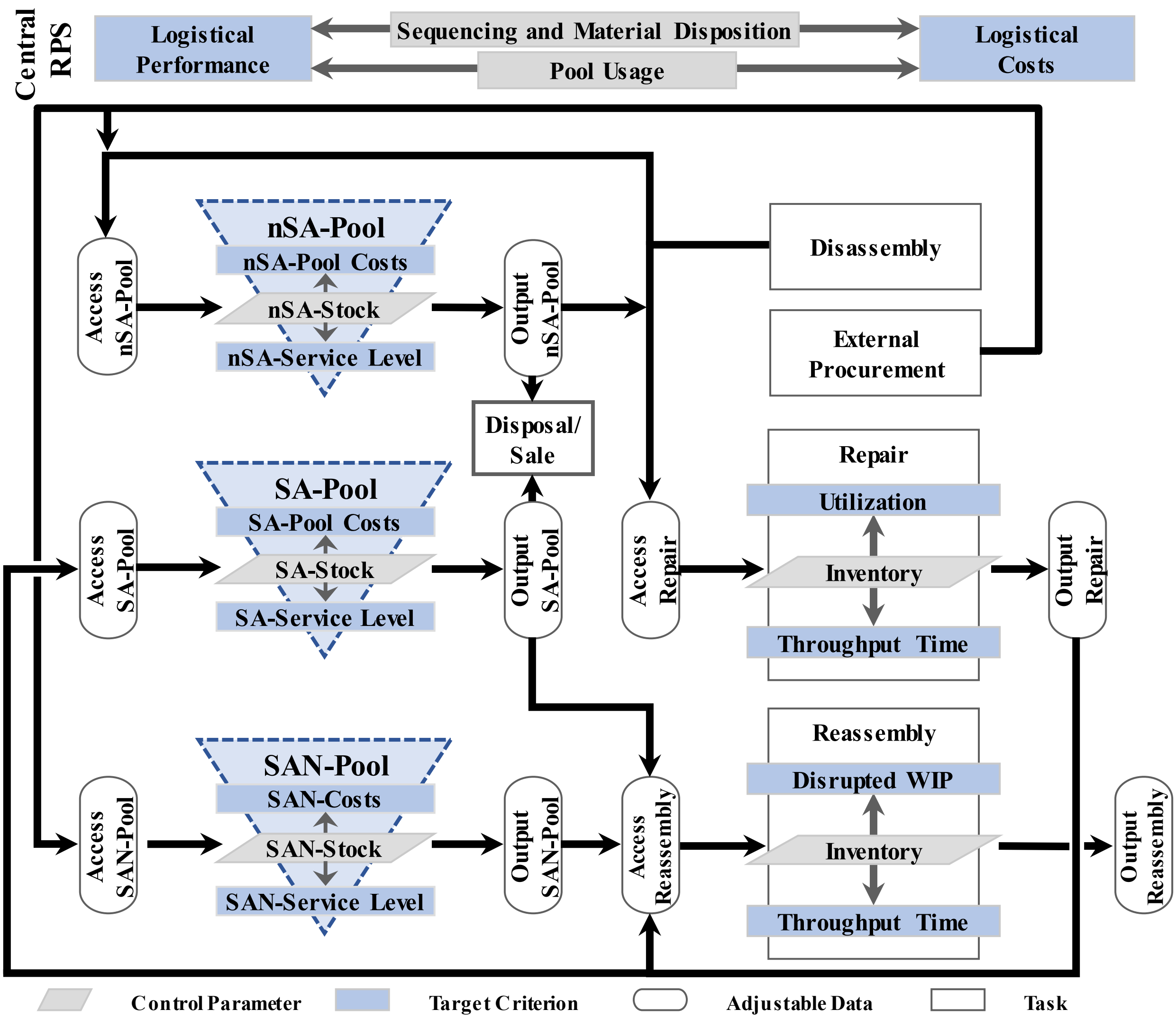

Figure 2: Interaction model of the regeneration supply chain

From disassembly, components can either go into the nSA-pool or repair. The output of the nSA-pool also provides access to the repair. In repair, an inventory is built up that includes both repair stock and WIP, since not all components can be processed immediately due to limited repair capacity. However, the stock of components in repair also influences capacity utilization, since an appropriate stock means a good relation of high utilization with suitable throughput times for components waiting for their repair [10]. After the components have been processed in repair, they are forwarded as the output of repair. Subsequently, components are ready for the time-critical reassembly and can be assigned directly to the access of the reassembly. Reassembly depends on a large number of very different components that converge to form the complex capital good. The direct path to reassembly is mainly used when a component has been repaired order-specific. Another possibility is that the repaired component gets stored in the SA-pool since the component has been repaired order anonymous.

In addition to the output of the disassembly, access to the nSA-pool is also impacted by the external procurement of components. An external procurement of nSA-components is worthwhile for the company if its repair is well developed, enabling low repair costs or if components are required for replacement. Access of the nSA-pool increases the nSA-stock. The higher the nSA-stock, the more the correlating nSA-pool costs. Though, the nSA-stock enables an increased nSA-service level for repair. All components taken from the nSA-pool are summarized in the output of the nSA-pool. Components from the nSA-pool can be sold or disposed of if an internal repair would not be feasible. The nSA-pool output passes into the access of the repair.

External procurement obtains new components. The access to the new components (SAN) pool affects SAN-stock in the new components pool. A higher SAN-stock increases current SAN costs and ties up capital due to high prices for new components. However, the SAN-stock has a positive impact on the SAN service level and, therefore, a positive effect on the schedule reliability of the reassembly. New components can be used immediately, mostly without compromise, and with full certification as a replacement in reassembly. However, external procurement is associated with procurement lead times and effort, which delays access to the SAN-stock. The output of the SAN-pool always goes directly into the access of the reassembly.

The SA-pool is integrated into the components flow to enable on-time delivery for reassembly. The output of repair feeds the access of the SA-pool. The difference between input and output of the SA-pool results in the SA-stock. On the one hand, stock means stockholding costs; on the other hand, it supports the SA-pool's service level to repair, decreasing disrupted WIP in reassembly. For this reason, the SA-pool is crucial to increase overall logistical performance in this model. Due to its excellent cost-efficiency, compared to the new components pool, the SA-pool is to be preferred as far as it is possible under consideration of legal and customer requirements. If the product range no longer requires them, components can also be sold or disposed of via the actual output of the SA-pool.

Moreover, the regulatory authority must plan and monitor all material flows. A central regeneration planning and control (RPS) is located above the nSA- and SA-pool, as well as the new components pool, and keeps track of repair to achieve optimized performance for reassembly. [22] The choice of the material disposition path and sequencing in the repair have to be coordinated centrally and - due to complexity and the high number of possible plans - simultaneously [13]. Deviations in the scheduled sequences delay components for reassembly and delivery delays may result in penalties. In contrast, the use of the pool system can help to maintain delivery date reliability when such issues occur. For this reason, the pools' stocks need to be planned. The RPS is intended to ensure that defined stocks in the pools do not fall below a certain threshold but do not generate a surplus. Using PUSH and PULL mechanisms, RPS can control the pools [23]. If, for example, the SA-pool reaches an average stock level, but utilization in repair shops decreases, the PUSH mechanism takes effect, and the nSA-pool provides the repair shop with components for processing at short notice. However, if the SA-pool stock decreases, a PULL mechanism requests repaired components of the repair stage. Thus, central control variables are the stocks in all stages.

4. Pool Dimensioning

After discussing the interaction model, one can conclude that pool stocks play an essential role in the regeneration supply chain. In addition to individual pool stocks, the relation of pool stocks is elementary. Works by KUPRAT and GEORGIADIS are concerned with the selection of components to be pooled. There are also approaches for calculating the optimal stock level of an SA-pool. Nevertheless, the relation between SA- and nSA-pool stocks and utilization of the regeneration supply chain is little discussed. [24,8] For this purpose, a qualitative relation is derived from the considerations of chapter 3 and displayed in Figure 3. In the diagram, axis labels S_{SA} and S_{nSA} represent the individual stock of the pools. The stock of the SA-pool is placed on the ordinate axis, that of the nSA-pool on the abscess axis. Furthermore, a safety stock in the SA-pool (SSL_{nSA}) and a safety stock in the nSA-pool (SSL_{nSA}) are marked. Three possible exemplary function courses of stock relations are shown, depending on future utilization in the repair and divided from a low to a higher future utilization level.

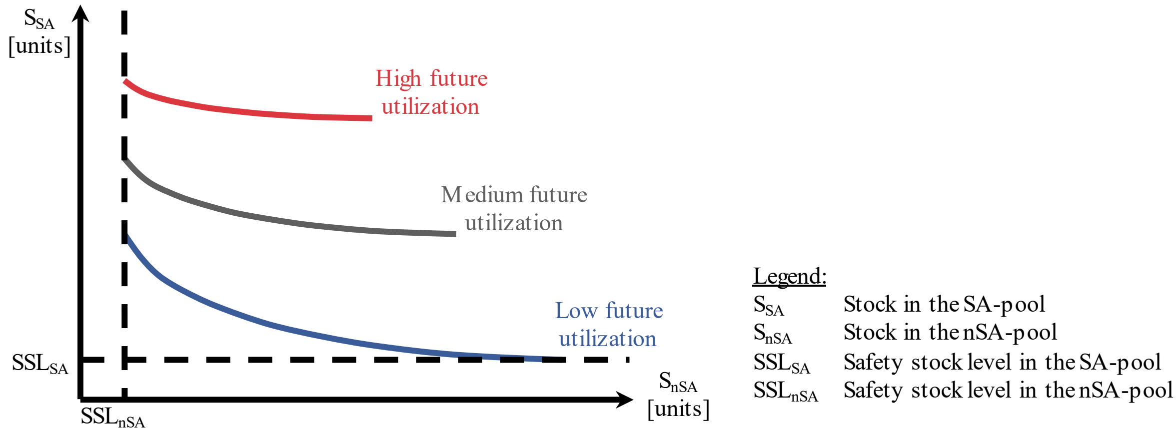

Figure 3: Corresponding SA- and nSA-pool stock dimensioning depending on utilization

A high utilization means an increased volume of work in the repair stage, but especially an increased number of complex capital goods to be reassembled. In order to ensure timely completion of required components in reassembly, despite the unpredictable and increased throughput times due to high load, an increased SA-pool stock must be available to avoid delayed components and, finally, delays of the complex capital goods. In this case, only the SA-pool can contribute to punctuality. Availability of nSA-components in the nSA-pool does not significantly influence the required stock of the SA-pool since nSA-components cannot be processed quickly enough in repair. Hence, the course function for high utilization is flatter than the course function for lower utilization. For the same reason the maximum amount of nSA-stock is limited on the abscess axis as well. In order to enable a higher SA-stock, an increased external procurement, or an increased output of the repair is necessary. With low actual utilization, so-called pre-production is possible, which increases the output of the nSA-pool and thus the input and output of the repair. During high utilization periods, the repair stage is supplied earlier by the nSA-pool with time-critical components, which are significant for the punctuality of the entire regeneration supply chain. The stock of the nSA-pool is decreasing as the provision of time-critical components for repair can be executed even before disassembly is finished.

In expectation of lower future utilization, to decrease stockholding cost, the SA-pool stock is reduced. Therefore, the course function of low utilization is lower. On the contrary, nSA-stock is built up because stockholding costs are lower, and due to lower future utilization, nSA-components can be repaired as required. Preferably, components stored in the nSA-pool can be used again and sent to repair when a high utilization is predicted. Due to the dynamic order situation, a safety stock in the SA-pool is essential. Safety stock in the SA-pool maintains flexibility and enables it to react as capacity utilization changes to ensure a high service level and, accordingly, high delivery reliability [15]. Besides, the nSA-pool maintains a safety stock, which makes it possible to increase utilization in the repair if the workload in the repair decreases.

A constant adjustment of the related stocks of pools depending on future utilization is necessary. Accordingly, a space between the minimum and maximum utilization is put up. With concrete calculations for the use case, a family of curves must represent a dynamic transition for potential cases between extremes. For the first consideration, the stock in Figure 3 is assumed for an exemplary component type. For different types of components, different course functions have to be developed. In addition, an assessment of costs must be carried out through the course of the curves for individual cases.

One problem in the interaction of SA- and nSA-pooling solutions is especially the matching of stocks of both pools [24]. Due to the mentioned close, indirect coupling of nSA- and SA-pool, corresponding stock fluctuations are expected. This, in turn, can counteract the original intention if components are not selected correctly. Too many pooling components lead to high logistical costs. Lower stocks diminish balancing effects of utilization and punctuality on the regeneration supply chain through the pools. On top of that, it will not be economical to build up pool stock for all components. For each use case analyses must be carried out to define components that are worth to be pooled [8].

5. Conclusion

This paper describes the possibilities of a regeneration supply chain with different pooling solutions, displaying the regeneration supply chain and its internal interactions, as well as pointing out the important aspect of pool stock dimensioning. Here, the regeneration supply chain is considered on an internal company level. First, SA- and nSA-pool are described, and their position in a regeneration supply chain is explained. Different effects on the regeneration supply chain without pooling, with an SA-pool or with an SA- and nSA-pool are presented. Additionally, already known approaches of regeneration supply chain pooling are explained. A solution with SA- and nSA-pool betters the logistical performance of the entire regeneration supply chain. In particular, the nSA-pool helps with a "utilization-oriented strategy", which balances the utilization in the repair shops, and the SA-pool helps with a "reassembly-oriented pooling strategy", which improves the punctuality of the reassembly. Also, expensive new components procurement is substituted as the only option for time-critical tasks. However, more logistics capacity and space is used, and more logistic planning is required.

In the presented regeneration supply chain interaction model, interactions of individual stages are explained. For pools, the pool stock is put into perspective with correlating pool costs and pool service levels. In the repair stage, repair inventory influences the throughput time and utilization. Inventory of the reassembly raises disrupted WIP and influences the throughput time in reassembly. Crucial interactions for the pooling layout are the output of the nSA-pool, which supplies the access of repair in order to influence utilization of the repair, and the access of reassembly, which is supported by the output of repair, SA-pool and SAN-pool, in order to enhance punctuality of the reassembly. These results can be used to align the regeneration supply chain design with the company's targets, improving logistical efficiency.

Moreover, the central regeneration planning and control influences schedule reliability and total costs by using the pooling infrastructure. Interactions within the regeneration supply chain for complex capital goods play an essential role in the dimensioning of pooling solutions. The pool stocks are related to each other and future utilization. In case of high future utilization, a high stock of the SA-pool is needed to enable quick support for the reassembly. In contrast, with low future utilization, the nSA-pool stock is higher, and the more capital binding SA-stock lower. Thus, low utilization allows a lower total stock level. The derived relations help the regeneration service provider to manage pool stocks according to forecasted utilization. For this purpose, relations of stocks need to be put into perspective for individual components, and a comprehensive strategy for possible situations needs to be developed. Here, more research is needed, and the next step would be to formulate specifications for regeneration planning and control to make the needed adjustments of pool stocks visible on the component level. The pooling design will be significantly specific to the considered application. Therefore, scaling is complicated. Finally, pooling solutions will need to be implemented and tested with data of a regeneration service provider, and especially the effect of the nSA-pool will require evaluation.

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Biography

Tammo Heuer, M.Sc. (*1992) studied industrial engineering at the Leibniz University Hannover and has been working as a research associate at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover in the field of production management since 2018.

Benedict Wildmann, B. Sc. (*1994) studies mechatronics engineering and has been working as a research assistant at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover since 2018.

Torben Lucht, M.Sc. (*1991) studied industrial engineering with the focus on production technology at RWTH Aachen University. Since 2018, he works as a research associate in the field of production management at the Institute of Production Systems and Logistics (IFA) at the Leibniz University Hannover.

Prof. Dr.-Ing. habil. Peter Nyhuis (*1957) studied mechanical engineering at Leibniz University Hannover and subsequently worked as a research assistant at the Institute of Production Systems and Logistics (IFA). After completing his doctorate in engineering, he received his habilitation before working as a manager in the field of supply chain management in the electronics and mechanical engineering industry. He is heading the IFA since 2003. In 2008 he became managing partner of the IPH - Institut für Integrierte Produktion Hannover gGmbH.