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Procedia CIRP 62 (2017) 153 – 158

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10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Combining in-house pooling and sequencing for product regeneration by means of event-driven simulation

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Abstract

The condition of complex products in the transport industry, such as train couplings or aircraft turbines, is not exactly determinable before their disassembly and diagnosis in a maintenance plant. Thus, planning and control of their regeneration is impeded since work plans and spare part demand result at short notice. This paper presents a novel method, which combines a planning approach, the in-house pooling of components, and a controlling approach, the sequencing of components, by means of event-driven simulation. Thereby, mean cycle time, mean tardiness and on-time delivery can be optimized under the consideration of the volatile conditions.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Simulation; Production planning and control; Sequencing

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1. Introduction

The rising complexity and value of products used in transport industry, e.g. train couplings or aircraft turbines, increase the importance of their regeneration [1]. However, the condition of the products is in many cases not determinable during their operation. Hence, their regeneration takes place in maintenance sites at defined intervals of time or mileage. The unknown condition of components before their disassembly and inspection in the site leads to dynamic work plans, uncertain processing times and lumpy spare part demand. Consequently, the regeneration planning and control (RPC) is impeded and result in fluctuating cycle times. Since the majority of German regeneration companies define the reliability of their services as their main goal, harmonizing cycle times and improving on-time delivery as well as mean tardiness has to be considered in particular [1,2].

Maintenance sites are organized as job shop productions, because they have to handle a wide range of products and a high rate of variants [3]. However, the material flows of different products' individual components share the same buffer in front of the reassembly [4]. At this convergence point, the production material flow (repaired components) and the stock material flow (spare parts) merge to one, see Fig. 1.

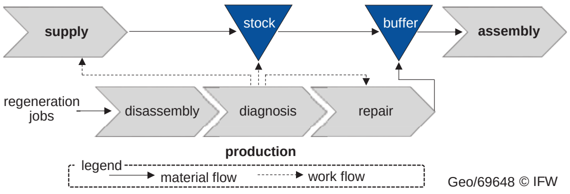

Fig. 1. Schematic procedure of a regeneration process.

Because the assembly only starts when the last component of a job arrives, cycle time, job tardiness and on-time delivery as well as the waiting work in progress (WIP) are primarily defined by this point in time. In particular, at the date required three categories of WIP are distinguished:

- completed WIP (assembly started on time)
- partial completed WIP (components waiting at the buffer)
- not supplied WIP (needed components, which have not arrived yet at the buffer)

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2016.06.005

The value of waiting WIP over a period under review, e.g. one year, is in the following referred to as distorted WIP. The higher the distorted WIP the more capital commitment costs for the regeneration company occur due to not completed assemblies. Thus, there is a need for RPC methods, which synchronize the provision of components to the assembly on time. In doing so, the service performance is increased and the distorted WIP reduced [4].

Based on the investigations of [5,6] it emerged, that the planning method “pooling” and the control method “sequencing” have a strong influence on the performance of regeneration companies. Thereby, the dynamic and stochastic dependencies among the consecutive regeneration steps, e.g. between the diagnosis and the repair process, have to be considered for an optimal coordination of the material flow. Prior research led to simulation-based pooling and sequencing approaches using the event-driven simulation [4,6]. However, the combination of these methods has not been investigated yet.

This paper illustrates the state-of-the-art of pooling and sequencing. Afterwards, the method of combined in-house pooling and sequencing is introduced. The method is implemented and tested in an event-driven simulation of a real case scenario, the regeneration of train couplings.

2. State of knowledge

The following section presents the difference between external product pooling and in-house component pooling as well as the results of previous simulation studies on sequencing in the field of product regeneration.

2.1. Disposition of pool-inventory

Research on the disposition of pool inventory has been carried out in the economic literature, particularly for the aircraft industry, since the end of 1960 [7]. The idea is, that worn out products are regenerated in maintenance sites and directly supplied to external warehouses (pools) following the make-to-stock principle. The pools provide the stocked products to decentral locations for temporary storage or directly to their points of use. Thus, short transport and delivery times are realized. On the other hand, additional inventories are built up and particular attention must be devoted to the emerging inventory and transport costs [8, 9]. Since the pools are located outside of the regeneration sites and store completely regenerated products, this method is defined as external product pooling [7]. External pooling approaches consider the regeneration process as a “black box” and approximate cycle times via exponential or Poisson distributions. Furthermore, infinite repair capacities are assumed and dynamic as well as stochastic cause-effect relationships in the site neglected [8,9,10]. Hence, in [4] a simulation-based approach is developed, which transfers the idea of external product pooling to the pooling of components in a regeneration site (in-house), see Fig. 2.

Components of products that regularly induce delays to the start of assembly, e.g. because of long processing times, are systematically identified by means of the event-driven simulation and added to the pool (pool-components). As a result, they are supplied to the assembly on time.

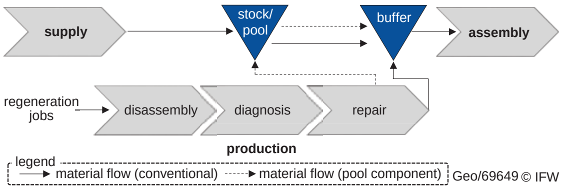

Fig. 2: In-house pooling of components at the product regeneration.

The regeneration process is not affected since repaired pool-components fill the pool after their regeneration to create a closed circuit. Mean cycle time, mean tardiness and on-time delivery are greatly improved. The benefits have to be contrasted with the initial acquisition and stock costs. Because of this optimization problem, Georgiadis et al. [4] introduces a method to determine pool configurations under economic aspects (suitable components, optimal stock-sizes).

2.2. Sequencing

Sequencing rules are used to determine the priority of a job or component at waiting queues in the production. Table 1 describes five rules, which are frequently tested at assembly job shops and repair shops. Assembly job shops are characterized by a job shop production with convergent material flow to an assembly, but do not consider a disassembly or diagnosis. These specific regeneration steps are considered in repair shops.

Table 1: Sequencing rules tested in assembly job shops and repair shops.

Rule	Full Rule Name	Description
RAND	Random	A random job or random component is processed first.
FIFO	First-In, First-Out	The job or component which arrives first at the work station is processed first.
SPT	Shortest Processing Time	The job or component with the shortest operation processing time is processed first.
EDD	Earliest Due Date	The job or component with the earliest due date is processed first.
JST	Job Slack Time	The job or component with minimum slack is processed first.

Sequencing at assembly job shops has been well studied over the last decades [11]. In contrast, sequencing in repair shops has not received the same attention.

Guide et al. [12] investigate the influence of the rules FIFO, SPT and EDD in repair shops with different utilization level, number of machines and product complexity. They identified that the utilization level of machines and the complexity level of products have a strong influence on the impact of sequencing in repair shops. The best results concerning mean tardiness and on-time delivery were achieved by the EDD rule. However, at various settings, the improvement of the mean cycle time was better by using FIFO and SPT. Reményi et al. [2] tested the impact of the sequencing rules FIFO, EDD and JST on the regeneration of aircraft engines by using an event-driven simulation. The best results regarding cycle time and on-time delivery were achieved by the combination of FIFO and JST.

Georgiadis [6] used the event-driven simulation to develop a specific sequencing rule for the product regeneration, named Fix-And-Continue-Algorithm (FACA). This rule identifies delayed components at the assembly by means of the simulation and prioritizes them on their repair path. The impact of FACA was compared to the rules FIFO, SPT, EDD, JST and Longest Processing Time (LPT). It emerged, that EDD, JST and FACA lead to the best results concerning on-time delivery and mean cycle time. Mean tardiness was significantly improved by the FACA rule.

3. Combining in-house pooling and sequencing by means of event-driven simulation

The combined method of in-house pooling and sequencing consists of five main steps, see Fig. 3. At first, a simulation model of the considered real case scenario according to VDI guideline 3633 is developed and validated [13].

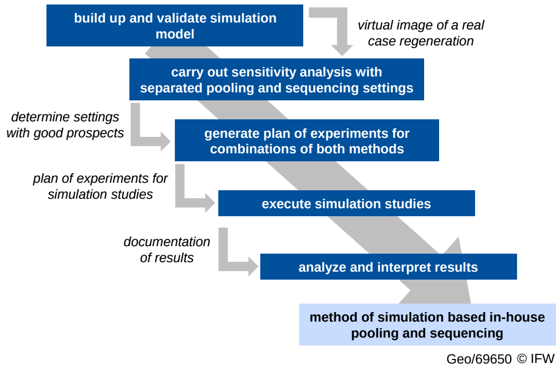

Fig. 3. Method of simulation-based in-house pooling and sequencing.

Within the research projects Celeritas and Smart Wheel Set, simulation models for two real case scenarios, the regeneration of train couplings and train wheel sets, were successfully build up and validated [4,14]. The models formed the basis for the implementation of in-house pooling and sequencing approaches [4,6]. Their modular design emerge the possibility to combine both approaches without great need for adjustment. However, the combination of approaches significantly increases the number of simulations since more variables have to be investigated.

One pooling scenario, for example, is defined by the selected pool components and their inventory level [6]. This specific setting can be combined with different sequencing rules at various utilization levels, see Fig. 4. In the second step of the method, a sensitive analysis is carried out to determine pooling and sequencing settings with promising prospects. In addition, the pooling approach of [4] must be adapted in order to determine economic pool configurations quickly, see section 3.1. Based on the results of the sensitive analysis, a time efficient design of experiments for the combination of pooling and sequencing settings can be set up. The plan describes the variables for the simulation experiments and the amount of simulation runs needed to guarantee statistically reliable results.

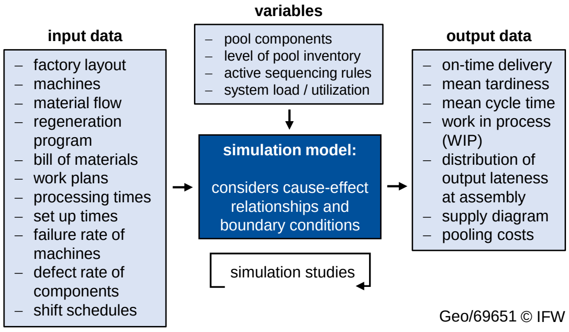

Fig. 4. Structure of the simulation model.

Subsequently, the simulation studies are carried out and the emerging results analyzed, e.g. by means of the indicators mean cycle time, mean tardiness and on-time delivery. Beside these performance indicators, the supply diagram is determined. The diagram visualizes the supply situation at the assembly, e.g. by showing the distorted WIP over the period under review or the completed WIP at the date required [15]. This enables the possibility to interpret the impact of the selected variables to the supply situation (synchronicity and punctuality of the supply processes) at the convergent point.

3.1. New pooling algorithm for sensitive analysis

Within the sensitive analysis, economic pool configurations must be determined quickly. Therefore, the in-house pooling approach of [4] is adapted by means of a new algorithm, which is described in the following.

The goal of the algorithm is to determine iteratively components that delay the scheduled start of assembly. For this purpose, the distribution of output delay of all components and supply processes is analyzed. In real case regenerations each product consists of more than 50 components. Additionally, at least two different supply sources exist (e.g. production, stock). Hence, component indicator CI_{ij} is developed to compare the distribution of all components and supply processes quickly, see (1).

$$CI_{ij} = \sum_{t=1}^{T_{\max}} \frac{t}{T_{\max}} \cdot input_{i,j,t} \tag{1}$$

With:	CI_{ij}	component indicator of component i and supply process j [-]	
	$input_{i,j,t}$	amount of components i of supply process j arriving at assembly with tardiness t [-]	
	$T_{\max}$	maximum tardiness of all supplied components [days]	
	i	component [-]	i=A, Aa, Ab,…, ZZ
	j	supply process [-]	j=1, 2 1: production; 2: stock

t tardiness [days] t=1, 2, 3, …, n

The function of the calculation rule (1) is described by means of an example, see Fig. 5.

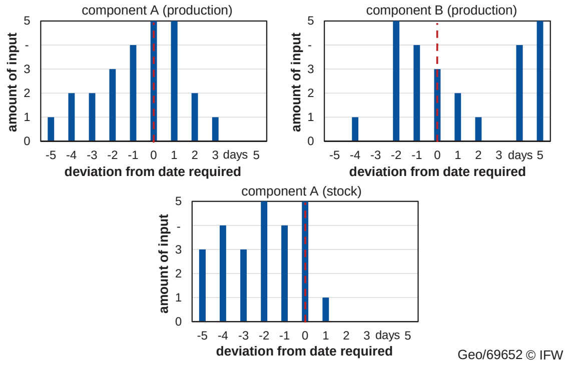

Fig. 5. Exemplary distributions of output delay.

Component A from the production arrives at the assembly with short delays. In case of irreparable defects, the same component is supplied from the stock regularly on time. Component B from the production, in contrast, arrives with long delays. Consequently, a pool inventory for this component leads to a great improvement of the service performance. Table 2 shows the results of the calculated CI_{ij}.

Table 2. Calculated values for component indicators.

Component i	Supply process	component indicator [-]
A	1	2.4
A	2	0.2
B	1	9.0

Based on this information, the algorithm increases the pool inventory of component B $I_{pool,i=B}$ by one unit and simulates the updated setting to determine iteratively further increases of the pool inventory, see Fig. 6.

For each setting, mean cycle time, mean tardiness and on time delivery as well as WIP and pooling costs are documented and stored to a database. The results of the sensitive analysis for the real case scenario, the regeneration of train couplings, are shown in section 3.3.

3.2. Real case scenario - regeneration of train couplings

In the following, the real case scenario is presented. The regeneration company maintains more than 80 different couplings at its maintenance site, which consist of 55 up to 405 individual components. As 80 couplings cannot be simulated due to long simulation time, two specific types are investigated, see Table 3. Coupling 1 is a semi-permanent coupler with an average degree of complexity, built up of 55 components. In contrast, coupling 2 consists of 405 components. The large variety of parts leads to a high level of complexity and great regeneration effort.

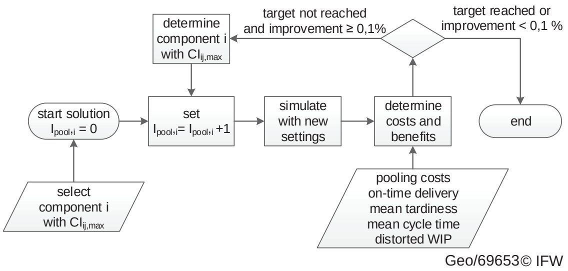

Fig. 6. Algorithm to determine economic pool inventories.

Hence, the annual amount is lower and the mean cycle time higher in comparison to coupling 1. This fact is important since the influence of stochastic parameters, such as defective components or machine failures on the cycle time, is higher. Consequently, the results from the simulation are more fluctuating.

Table 3. Basic information of simulated coupling types.

Coupling	Amount of individual components	Annual work load [amount of couplings]	Level of complexity
Type 1	55	200-250	medium
Type 2	405	15-25	high

20 simulations for each parameter setting are run to identify tendencies for all pooling and sequencing configurations. Promising sequencing and pooling settings, afterwards, are combined and tested by 60 simulations in order to ensure statistically robust results.

3.3. Results of the sensitive analysis

The first simulations of the sensitive analysis are made to determine pool configurations under economic efficiency. Thereby, the new pooling algorithm of section 3.1 is simulated for a review period of two years, see Fig. 7. The graph depicts the results for coupling 1 by showing the development of the mean cycle time and on-time delivery as a function of the increasing pool inventory, respectively the total pooling costs.

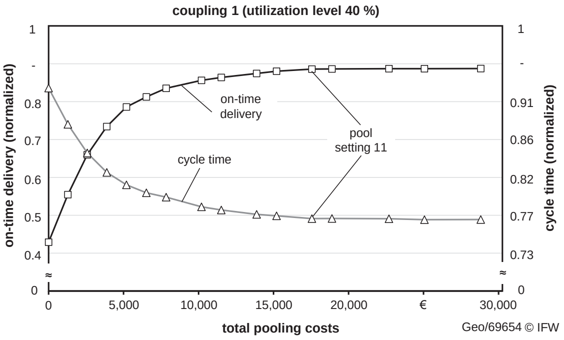

Fig. 7. Results of the pooling algorithm for coupling 1.

Pool setting 11 consists of 8 bearing brackets and 3 tie rods. The setting constitutes a good compromise between a high improvement of the service performance and the emerging pooling costs. On the one hand, mean cycle time decreases by 17 % and on-time delivery increases by 107 %. On the other hand, total pooling costs of approximately 17,500 € occur. 97 % of these costs relate to the acquisition of new components for the initial pool inventory. This means that with an increasing review period relative pooling costs will decrease.

Fig. 8 depicts the results for coupling 2. The emerging diagram shows comparable tendencies to coupling 1. The algorithm, however, determines a significantly lower amount of pool components and lower improvement of the performance.

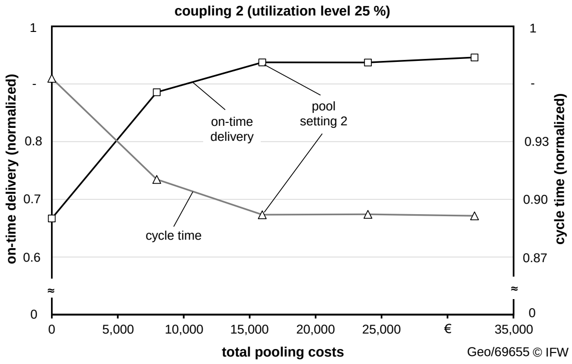

Fig. 8. Results of the pooling algorithm for coupling 2.

There are multiple reasons for this:

- only one critical component (coupler head case)
- high acquisition costs for the critical component
- lower amount of annual work load
- higher service performance at the initial state

Pool setting 2 consists of 2 coupler head cases. It improves the mean cycle time by 8 % and the on-time delivery by 41 % by inducing total pooling costs of approximately 16,000 €. Thus, it is recommended to be combined with sequencing rules, see section 3.4, which are determined by using the sensitive analysis.

The results for coupling 1 at two utilization levels (initial state: 40 %, increased job workload: 50 %) are presented in Fig. 9. At the utilization level of 40 %, FACA rule leads to the best results. The cycle time improves by 2 %, on-time delivery increases by 7 % and mean tardiness as well as the distorted WIP decreases by 16 % and 4 %. The rules EDD and JST lead to similar results, whereas SPT rule performs poorly.

By adding new regeneration jobs to the system, the utilization level is increased to 50 %. This fact leads, on the one hand, to very poor results of the SPT rule since the cycle time increases by 15 % and mean tardiness by 250 %. On the other hand, EDD, JST and FACA rule lead to the best outcome again. The poor performance of the SPT rule is because components with long processing times are regularly supplied late to the assembly. Thus, job completion is delayed. At the utilization level of 50 %, JST rule performs slightly better than FACA and EDD rule.

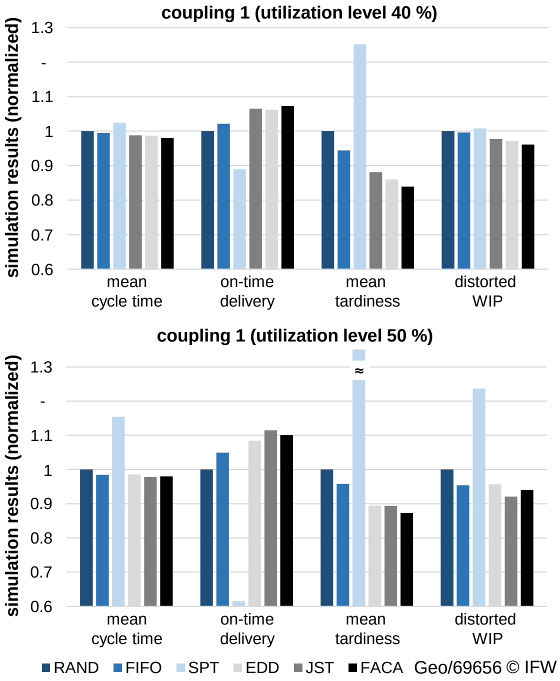

Fig. 9. Impact of sequencing rules at two utilization levels for coupling 1.

Fig. 10 depicts the outcomes for coupling 2 at the utilization levels of 25 % (initial state) and 30 % (increased job workload).

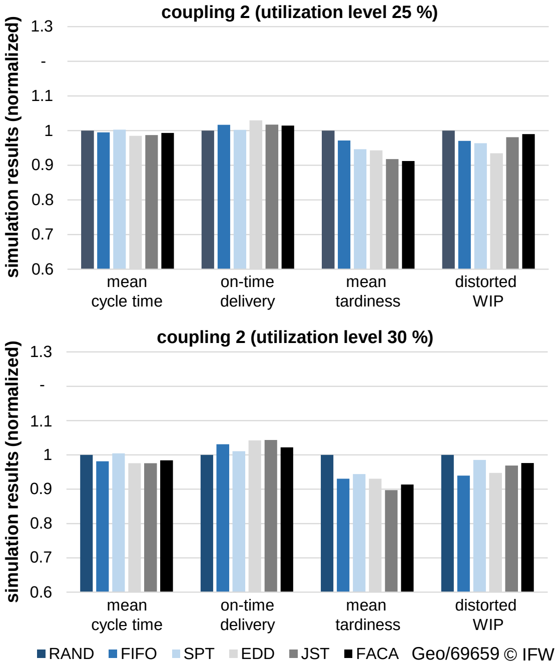

Fig. 10. Impact of sequencing rules at two utilization levels for coupling 2.

In comparison to coupling 1, the annual work load and utilization levels are lower. Thus, the impact of sequencing is also lower. However, FACA, EDD and JST rule improve the service performance, in particular, mean tardiness. Since these rules lead to the best results for both coupling types, they are tested in combination with the economic pool configurations.

3.4. Results of combining in-house pooling and sequencing

Based on the outcomes of the sensitive analysis, the economic pool scenarios (coupling 1: setting 11, coupling 2: setting 2) are combined with the effective sequencing rules EDD, JST and FACA. The combinations are tested by means of 60 simulation runs at the initial utilization level (coupling 1: 40 %, coupling 2: 25 %) and averaged, see Table 4.

Table 4. Results of combining pooling and sequencing.

Coupling type	Simulation settings	cycle time	on-time delivery	mean tardiness	distorted WIP
Type 1	Pool + RAND	-17 %	+106 %	-89 %	-60 %
	Pool + JST	-18 %	+109 %	-90 %	-64 %
	Pool + EDD	-18 %	+108 %	-90 %	-63 %
	Pool + FACA	-17 %	+107 %	-90 %	-62 %
Type 2	Pool + RAND	-8 %	+40 %	-86 %	-46 %
	Pool + JST	-9 %	+42 %	-90 %	-47 %
	Pool + EDD	-8 %	+41 %	-89 %	-50 %
	Pool + FACA	-8 %	+40 %	-88 %	-46 %

The results confirm that pooling improves greatly the service performance. Mean cycle time is reduced by more than 8 %, mean tardiness decreased by more than 86 %, on-time delivery increased by more than 40 % and distorted WIP reduced by more than 46 %. The combination of pooling and sequencing provide a possibility to improve the high service performance further without additionally costs. Although the impact of sequencing slightly decreases in comparison to its separated application, JST and EDD rule improve both pooling scenarios. FACA rule has no effect on the performance since the prioritized components are supplied already from the pool. The impact of the most effective separated and combined approaches on the timely provision at the assembly is shown by analyzing the proportion of the WI P at the date required, see Fig. 11.

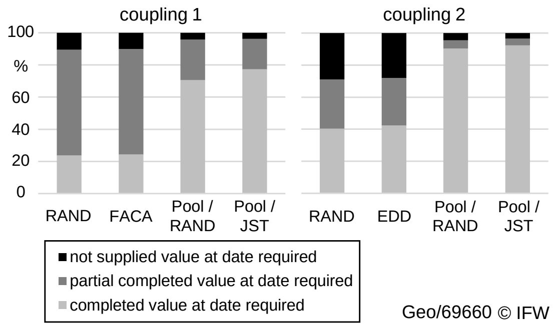

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Fig. 11. Proportion of WIP at date required.

Sequencing and pooling approaches as well as their combinations, increase the proportion of completed WIP and decrease the proportion of not or partial supplied WIP at the date required. Thereby, the combination of pooling and sequencing increase the value of completed WIP to 77 % for coupling 1 and 93 % for coupling 2.

4. Conclusion and outlook

Regeneration companies have to deal with unknown condition of products' individual components and dynamic material flow. Therefore, timely provision of components to the assembly is impeded, even though it is urgently needed since long waiting times reduce the service performance. To improve this situation a new method, the combination of simulation-based pooling and sequencing, is developed and tested for a real case scenario. The method optimizes the timely provision and greatly improves the service performance. Since the combined method has only been tested at the initial utilization level, further research should test the impact of the approach at different utilization levels.

Acknowledgements

The authors thank the German Ministry of Economics and Energy for its financial an organizational support of the project "CELERITAS – System for the acceleration of production processes" under the program ZIM-Coop (Central Innovation Program, funded in co-operation).

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