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A Priority-Rule-Based Approach for the Dynamic Control of Reassembly in Matrix-Remanufacturing Systems

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Abstract

Remanufacturing is confronted with a high degree of inherent uncertainty, particularly during core disassembly. Variability in disassembly propagates into reassembly as parts arrive unpredictably, due to task failures or damaged components, yielding a dynamically changing pool of parts that defies fixed planning. Moreover, individual components may be compatible with multiple final-product variants, vastly expanding the matching possibilities. As a result, during reassembly, unpredictably arriving components have to be dynamically allocated into reassembly sequences and station assignments, as fixed planning is infeasible. The aim of this paper is to design and assess a priority-rule-based control approach for dynamic reassembly in matrix-remanufacturing systems facing uncertain component availability. The production control evaluates incoming components to form feasible pairs and determine the reassembly sequence, while an allocation agent assigns these pairs to workstations. We compare a suite of domain-specific priority rules and introduce a novel reassembly-specific priority rule via discrete-event simulation across scenarios of increasing variant and layout complexity, assessing their impact on throughput, work-in-progress, and station utilisation. Results show that the selection of priority rules had a significant effect on both performance and system stability. Results indicate that the reassembly-specific priority rule increasingly outperforms the conventional one as complexity rises. Nonlinear interactions between matching and allocation decisions become more pronounced as variant diversity and system complexity grow. By focusing on the interplay between uncertain disassembly outcomes and dynamic reassembly, the paper addresses a previously relatively unexplored problem statement in remanufacturing.

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1. Introduction

In light of global challenges, including resource depletion and the societal pursuit of sustainability, a transition to circular business models is increasingly necessary [1, 2, 3]. Especially remanufacturing serves as a promising alternative to linear production by creating closed material cycles and thus decoupling economic growth from the consumption of natural resources [3]. As an advanced recovery process, remanufacturing aims to reinstate end-of-use products to equal or higher functionality [4], thus extending their life cycle and safeguarding the embodied energy and materials [5, 6].

The remanufacturing process follows three sequential and interrelated steps: disassembly, reprocessing, and reassembly. During disassembly, end-of-use products are taken apart into their individual components and subjected to inspection. The usable components are subsequently restored to like-new condition, and in the reassembly phase, these reprocessed components are reassembled into new products [7, 8]. Typical products suitable for remanufacturing are characterised by a high value-density, such as automotive parts, power tools or household appliances.

Implementing remanufacturing systems on an industrial scale entails considerable complexity, driven by uncertainty in

both the quality and availability of end-of-use products and previously reprocessed components [9]. In this context, circular factories function as flexible and reconfigurable matrix-production systems consisting of interconnected modular stations [10]. The underlying premise is that adaptability and flexibility enable the system to cope with uncertainties more effectively. An equally modular and flexible control architecture complements the system, ensuring the full potential of its capabilities is exploited [11].

Nevertheless, the uncertainty associated with processing end-of-use products necessitates the implementation of advanced decision-making mechanisms within circular factories to ensure efficient resource utilisation and reliable delivery performance [12]. Although substantial research addresses the control of disassembly subsystems, comparatively little attention has been given to the production control of reassembly systems. While controlling reassembly systems may initially appear similar to managing linear assembly systems, the task differs significantly when the subsystem is embedded within a circular factory executing the entire remanufacturing process chain. Unlike conventional linear assembly systems, reassembly must contend with uncertain and non-deterministic component availability, a direct consequence of variability in disassembly outcomes. This necessitates production control strategies that dynamically match components for reassembly in a situation-dependent manner [8, 13]. Furthermore, since reprocessed components can be reassembled into multiple possible end products, the requirements for production control become even more demanding [7].

This paper presents a priority rule-based control system that effectively addresses the high uncertainty in component supply resulting from the stochastic nature of the upstream disassembly process. For this, a novel reassembly-specific priority rule is introduced and validated in conjunction with established priority rules. Following this motivating introduction, section 2 presents the related work and elaborates on the research gap. Subsequently, section 3 introduces the proposed approach, including a detailed description of the simulated production system. Section 4 presents the results, and Section 5 provides an overall performance evaluation, identifying potential future improvements.

2. Related work

Only a limited number of research approaches address the control of remanufacturing systems, and none fully consider the combined decision-making requirements of component matching and station allocation while accounting for the unique characteristics of remanufacturing, such as system flexibility, station redundancy, component commonality, and the need for dynamic decision-making.

Several studies focus on disassembly control as a critical upstream process. A heuristic multi-priority-rule approach combined with an optimisation tool for adaptive reparameterization of agile disassembly systems is presented in [14]. Their method employs a weighted priority function to dynamically assign disassembly orders to stations, with

weights adapted in real time to ensure optimal material flow. The approach is implemented using a discrete-event simulation of a redundant disassembly system.

Research on holistic remanufacturing scheduling has also received attention. A method for integrated scheduling across the entire remanufacturing system is proposed in [7], explicitly considering component commonality so that remanufactured components can be reassigned independently of their original product. They formulated a mathematical optimisation model, solved using a genetic multi-criteria algorithm, to maximise production efficiency.

Other studies address station allocation and job sequencing under different system configurations [13, 15, 16]. They investigate flow-shop, job-shop, and parallel workstation settings. These works focus on minimising delay or lead time through the use of mixed-integer optimisation models. In [13] the problem is decomposed into subproblems and solved with specialised algorithms, while [15] evaluate both individual and combined priority rules via simulation. Various heuristics are employed in [16], including priority rules, and their performance is compared.

This line of work is extended by [8, 17], addressing flexible job-shop scheduling for reprocessing with parallel disassembly and reassembly stations, though without component commonality. Their objective is to minimise throughput time and energy consumption. They formulate mixed-integer optimisation problems that are solved using metaheuristics, namely the Improved Grey Wolf Optimiser (IGWO) and the Improved Artificial Bee Colony algorithm (IABC).

Foundational work by [18] explored release mechanisms and priority rules for disassembly scheduling in simple systems without flexibility or redundancy. Later, [19] modelled a holistic remanufacturing system as a queueing network and compared several priority rules using simulation-based performance evaluation.

Beyond remanufacturing, there is extensive research on control of linear production systems [20, 21, 22]. Several of these works investigate dynamic order allocation to workstations in flexible and redundant systems, using discrete-event simulation to evaluate priority rules.

In summary, while the existing literature offers valuable insights into disassembly control, holistic scheduling, and priority-rule-based production control, there remains a clear research gap. Specifically, no approach simultaneously addresses dynamic component matching and station allocation under conditions of flexibility, redundancy, and component commonality in reassembly systems. This paper aims to close this gap by introducing and benchmarking a priority-rule-based control system tailored to these requirements.

3. Approach

The proposed control system builds upon the system architecture illustrated in Figure 1. It comprises a model of the matrix remanufacturing system, including an executable discrete-event simulation. As this paper focuses specifically on the control of the reassembly system, the upstream disassembly and reprocessing stages are deliberately represented as a black-

box model. This modeling choice isolates the effects of reassembly control by stochastically supplying components, thereby enabling a focused and unbiased evaluation of production control strategies. The production control system is responsible for managing material flow and ensuring the effective utilisation of available resources.

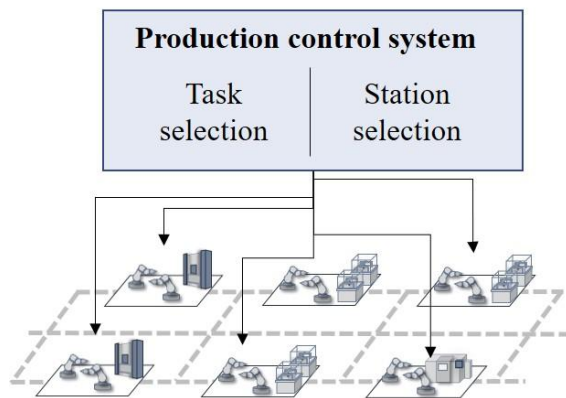


Fig. 1. Overview of system architecture

3.1. System model

The reassembly system seeks to fulfill a set of orders $O = (o_1, o_2, \dots)$, where each order corresponds to one of several possible final-product variants. Its primary objective is to maximise the number of fully reassembled orders within an eight-hour shift. To fulfil these orders, the system is supplied with components stochastically. The set of all components is denoted as $C = (c_1, c_2, \dots)$. The assembly of two or more components forms a subassembly. Let $Sub = (sub_1, sub_2, \dots)$ denote the set of all possible subassemblies required for reassembling any variant in O . To complete an order $o_l \in O$, a sequence of reassembly tasks must be executed. The set of all such tasks across all orders is given by $Tsk = (tsk_1, tsk_2, \dots)$. A task is defined on a per-product-instance basis, meaning that executing the same reassembly step on different instances of the same component type constitutes different tasks. At any given time, depending on the current state of a component c_l or subassembly sub_l and the availability of its required counterparts, only a subset of tasks can be executed. This set of feasible tasks is denoted as $Tsk_{l,possible} = (tsk_{1,possible}, tsk_{2,possible}, \dots)$.

Reassembly tasks are performed by a set of stations $S = (s_1, s_2, \dots)$. Each station s_j is characterized by its capability set $Cap_j = (tsk_1, tsk_2, \dots)$, while the set of stations capable of executing task tsk_i is represented by $Enab_i = (s_1, s_2, \dots)$. The execution of a specific task tsk_i on a station s_j is referred to as an operation. The redundant distribution of capabilities across stations creates a high degree of flexibility and responsiveness within the system.

It is important to note that during the reassembly process, the final product configuration for a particular component remains undetermined until the final assembly step is executed. This is because subassemblies belonging to different orders may overlap, meaning that the same intermediate subassembly can potentially be used in multiple final-product variants.

Consequently, the exact allocation of components and subassemblies is only finalised at the end of the reassembly.

To illustrate the complexity of the reassembly process and the resulting decision-making requirements, Figure 2 presents an exemplary bill of materials (BOM) for multiple final product variants. Each letter denotes a distinct component. The figure highlights how elements can be combined into intermediate subassemblies, which in turn can be further assembled into multiple alternative final orders. This overlapping structure illustrates that subassemblies may be shared across different product variants. As a result, the allocation of components to specific orders remains undecided until the final assembly step is executed, reinforcing the need for dynamic component matching and flexible production control.

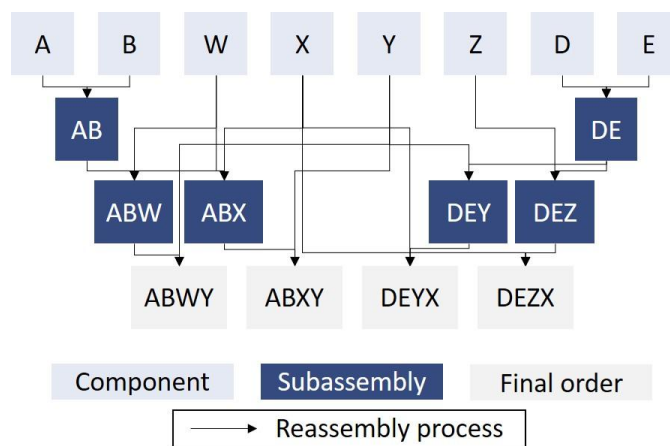


Fig. 2. Schematic illustration of reassembly sequences

Each station is equipped with an input and output buffer of limited capacity to decouple material flows. Stations process orders in their input buffer according to the FIFO principle. Once a reassembly task is completed, the resulting subassembly or final product is placed in the station's output buffer. Each station can process only one task at a time, and once started, an operation is executed without interruption until it is completed.

If no feasible task exists for a component or subassembly ($Tsk_l = \emptyset$), it can be temporarily stored to prevent input and output buffers from becoming blocked. Material handling between stations is carried out by Automated Guided Vehicles (AGVs), providing a flexible transport solution for components and subassemblies.

3.2. Priority Rule Approach

Components or subassemblies within the production system that are not yet fully assembled into final orders require a subsequent reassembly task and an appropriate station to execute it. This decision is addressed through a two-step approach. First, the following required reassembly task is identified, along with its corresponding counterpart component or subassembly. Based on the availability of these counterparts and the product structures of the outstanding orders, the set of feasible tasks is narrowed down to $Tsk_{possible} = (tsk_1, tsk_2, \dots)$. From this set, the production control agent

must determine which task to execute. For this purpose, different priority rules are applied, each assigning a score to the tasks in $Tsk_{possible}$ based on a rule-based formula. In the event of a tie between two or more tasks, one is selected randomly as a tie-breaker. Two established priority rules from production science, along with one novel rule specifically designed for reassembly systems, were implemented and compared with respect to their effectiveness:

The **Shortest Processing Time (SPT)** rule evaluates tasks according to the average processing time of the corresponding operation. This priority rule is widely applied in production planning. However, conventional implementations typically rely on deterministic processing times. In contrast, our approach incorporates the characteristic uncertainty of remanufacturing by using a value derived from historical data. Specifically, a rolling average of the processing times of the most recent executions of tsk_i is computed and denoted as tsk_i^{avg} . Tasks are then prioritized according to:

$$select^{SPT} = arg \min tsk_i^{avg} \quad (1)$$

The **Earliest arrival date (EAD)** rule prioritises tasks based on how long the corresponding order or subassembly has been waiting in the reassembly system to proceed to its next processing step. The underlying idea is to minimise average lead time. Let wtg_i denote the waiting time of the corresponding component or subassembly, measured either since its last reassembly operation or, if it has not yet been processed, since its entry into the production system. Tasks are then selected according to:

$$select^{EAD} = arg \min wtg_i \quad (2)$$

The **Highest Bill-of-Material Level (HBL)** is a reassembly-specific priority rule that selects tasks that are closest to completing an order. The rationale is that components or subassemblies that are nearly fully reassembled should be prioritised for completion before initiating new subassemblies. Let bml_i denote the minimum number of remaining reassembly operations required to complete the order. Tasks are then prioritised according to:

$$select^{HBL} = arg \min bml_i \quad (3)$$

Once a task tsk_i has been selected, a corresponding station must be chosen to execute it. Preliminary trials showed that the **Lowest Buffer Utilisation (LBU)** rule consistently outperformed all other alternatives. Therefore, for the sake of simplicity, only the LBU rule is applied in all experiments to allocate tasks to stations. According to this rule, the station s_j with the smallest number of orders waiting in its input buffer $ocup_j$ is selected for task execution. This corresponds to:

$$select^{LBU} = arg \min ocup_j \quad (4)$$

The combination of the selected task and the chosen station constitutes an executable decision, which is subsequently communicated to the shop-floor level for implementation.

The priority rules considered in this study can be viewed as a representative selection of rules targeting both time-based objectives, such as minimising lead time, and system-level metrics, such as maximising throughput. Naturally, other priority rules could be integrated into the control system. However, given that this paper aims to evaluate the general effectiveness of a priority-rule-based approach and to benchmark the newly proposed HBL rule against established alternatives, the selected rules are deemed sufficient for the scope of this study.

4. Results

The following section provides an overview of the experimental setup and presents the results of the simulation study. First, the three use cases are introduced, outlining how system and product complexity are systematically varied. Subsequently, the performance of the different priority rules is compared across these scenarios, with particular emphasis on the newly introduced Highest Bill-of-Material Level (HBL) rule.

4.1. Experiment setup

To evaluate the effectiveness of the proposed approach, three use cases were defined that progressively increase the level of complexity faced by production control. Complexity in this context refers to both the configuration of the production system and the structure and variety of products to be reassembled.

On the production system side, complexity is varied by modifying the number of stations within the system and by adjusting the degree of process redundancy. A higher level of redundancy, i.e., when more stations are capable of executing the same task, provides production control with a larger set of possible operations from which to select. While this enhances flexibility, it also increases the complexity of the assignment decision.

From a product perspective, complexity can be increased by raising the number of order types to be reassembled, as well as by increasing the number of components that constitute each product. Naturally, a higher number of components per order correlates with a greater number of reassembly tasks required for completion.

The three use cases were designed to analyse the performance of the production control system under these varying complexity levels. A comprehensive overview of the differentiating features of the use cases is provided in Table 1.

The production systems were implemented as discrete-event simulations in Python. Performance was evaluated over an eight-hour production shift. Given the stochastic nature of the model, 20 independent replications were conducted, and the results were averaged to obtain representative performance measures.

Table 1. Differences between use cases

System characteristic	Low	Medium	High
Amount of component types	8	12	12
Amount of order variants	6	10	10
Amount of stations	20	42	48
Amount of needed reassembly steps	3	5	6-7
# of capable stations per task	2	3	4

4.2. Evaluation

To assess the performance of the priority rules, several key performance indicators (KPIs) are considered. Overall system performance is evaluated using total system throughput. In addition, the mean order lead time is measured, providing insights into the time span between a component's arrival in the production system and the completion of the order into which the component is reassembled.

To determine whether specific components are disadvantaged in the process and remain within the system for extended periods, the mean age of unfinished orders at the end of the shift is calculated. This metric indicates the average time that unfinished components have spent in the system since their arrival.

The average results for the three use cases are summarised in Tables 2-4, together with each KPI's deviation from the best-performing priority rule.

Table 2. Low complexity case

Key performance indicator	EAD	SPT	HBL
Total throughput	666.1 (0.0%)	658.85 (1.1%)	662.3 (0.5%)
Mean order lead time	60.2 (1.5%)	59.5 (0.5%)	59.2 (0.0%)
Mean unfinished order age	134.9 (0.0%)	139.6 (3.5%)	138.4 (2.6%)

Table 3. Medium complexity case

Key performance indicator	EAD	SPT	HBL
Total throughput	600.9 (0.4%)	603.15 (0.0%)	602.9 (0.1%)
Mean order lead time	38.3 (3.2%)	38.1 (2.7%)	37.1 (0.0%)
Mean unfinished order age	62.0 (0.3%)	61.8 (0.0%)	62.6 (1.3%)

Table 4. High complexity case

Key performance indicator	EAD	SPT	HBL
Total throughput	583.45 (0.7%)	580.85 (1.1%)	587.45 (0.0%)
Mean order lead time	39.2 (3.1%)	38 (0.0%)	38.1 (0.3%)
Mean unfinished order age	59.3 (1.0%)	63.3 (7.8%)	58.7 (0.0%)

The choice of priority rule has a significant impact on system behaviour across the three scenarios. As complexity increases, the differences between the rules become clearer.

HBL performs consistently well across all KPIs. In medium- and high-complexity cases, HBL delivers short lead times, remains competitive in throughput, and avoids the strong growth in unfinished order age observed for SPT. This demonstrates that prioritising orders closest to completion prevents the system from accumulating ageing WIP and supports a smooth flow.

SPT is competitive when the system is simple. However, as complexity rises, it tends to age unfinished orders, signalling WIP build-up and congestion. This aligns with the intuition that prioritising short tasks can starve nearly completed complex orders, which then occupy buffers and inflate downstream queues.

EAD can achieve high throughput in the most complex setting, but does not deliver the best lead time. Compared to EAD, HBL offers a more balanced outcome in terms of throughput, lead time, and unfinished order age, particularly as variant and routing complexity increase.

Overall, the patterns across Tables 2–4 confirm the effectiveness of the HBL rule. It scales to higher complexity by completing nearly finished orders sooner, thereby limiting the ageing of unfinished work and stabilising the flow while maintaining throughput at or near the maximum level in every scenario.

5. Conclusion and Discussion

The findings of this paper contribute to and extend prior research on production control in remanufacturing systems. Earlier work on disassembly and reprocessing demonstrate that priority-rule-based approaches can effectively mitigate uncertainty in upstream processes [14, 18], but these studies did not incorporate the combined decision-making demands of component matching and flexible station allocation under component commonality. In contrast to the optimisation-based scheduling approaches of [7, 8], which require complete information and static order sets, the proposed approach demonstrates that simple, real-time priority rules can stabilize throughput even under high stochastic variability. Moreover, while [14] showed that multi-priority-rule heuristics improve disassembly responsiveness, our results indicate that a reassembly-specific mechanism (HBL) outperforms established rules as system and product complexity increase. This aligns with findings from [19] who highlighted that priority-rule performance depends on system dynamics, but we extend their insights to highly flexible, variant-rich matrix-remanufacturing settings.

Collectively, the priority-rule-based approach presented in this paper provides an effective means of dynamically controlling material flow within the reassembly system. In particular, the newly introduced Highest BOM Level (HBL) rule demonstrates superior performance compared to conventional priority rules. Nevertheless, several limitations of the approach become evident upon closer examination of its performance.

First, the model does not account for varying demand levels among different order types. In its current form, the approach treats all order types as equally viable, which results in a nearly uniform production mix across variants in the simulation runs. In practice, however, demand for individual order types can differ significantly. Future work should therefore extend the priority rules to incorporate order-specific demand information, ensuring that production output aligns more closely with real-world requirements.

Second, the approach can be enhanced by combining multiple priority rules through a weighted scheme that balances their respective strengths. Such weighting could potentially average out the beneficial attributes of each rule, improving overall system performance. Given that the effectiveness of individual rules depends on the system configuration and product mix, adaptive adjustment of these weights represents a promising research direction.

In summary, the results demonstrate that the newly introduced HBL rule is an effective priority mechanism for reassembly control. By focusing on nearly completed orders, it improves throughput while preventing excessive WIP accumulation and stabilizing lead times. Its advantages become more pronounced as system complexity increases, making it particularly suitable for highly loaded, variant-rich environments. The findings highlight the importance of careful priority rule selection in reassembly systems and provide a promising direction for future adaptive scheduling approaches.

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