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Mathematical optimization model for remanufacturing scheduling with sequence-dependent setup times

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Abstract: Remanufacturing is a key player in supporting sustainable manufacturing methods, a regenerative economic model, and the equitable allocation of resources in the ever-evolving environment of sustainable development. Our study tackles the scheduling difficulties in remanufacturing to facilitate sustainable practices. Specifically, we concentrate on scheduling operations on a mixed assembly/disassembly line, taking into account sequence-dependent setup time to minimize makespan, considering its substantial impact on remanufacturing efficiency. This work explores a crucial scheduling problem in hybrid production lines, concentrating on a mixed-flow job-shop structure. These systems provide an NP-hard scheduling challenge since they have two types of operations that need to be processed through the same group of workstations in different directions. Our main goal is to reduce the makespan or the maximum amount of time it takes to complete all the jobs. A mixed integer linear programming model (MILP) specifically addresses the complexities of this remanufacturing scheduling problem. Our goal in using this method is to find the best solutions for different cases while giving priority to processing efficiency. Extensive testing results confirm the effectiveness of our proposed mathematical framework, showing it can consistently provide outstanding performance in various scenarios. In this work, the implementation of modified scheduling methodologies to meet sustainable development goals expands the study of remanufacturing scheduling. It also highlights areas that may require more research, such as integrating logistics and improving the energy efficiency of remanufacturing processes.

1 Introduction

Over the past few decades, resource extraction and consumption have tripled due to a considerable rise brought on by simultaneous increases in consumption, population growth, and economic development [1]. In addition, the waste output is increasing due to technological improvements resulting in shorter product life spans [2]. To slow the rate of environmental deterioration, we must make significant changes to how we consume and conduct business [3]. This entails establishing innovative strategies to reduce the use of energy and resources, as well as adopting sustainable practices that encourage the reuse of materials, the use of renewable energy sources, and energy-efficient operations [4]. Because of this, sustainability has become legendary in today's world, where climate change is the norm due to mounting social pressure and environmental concerns [5-7]. Sustainable development represents a promise of a better world without compromising the environment for future generations. The circular economy is considered a viable tool to achieve economic sustainability, as it aims to bring the industry back into harmony with the environment. As a result, the movement towards a circular economy represents a significant opportunity to reconsider the relationship between production, consumption, and resources. Moving to a circular paradigm involves changing the economic logic from the traditional linear supply chain to a closed-loop supply chain in which, in addition to the usual direct flow of goods (from material sourcing to production to distribution), a reverse flow of goods back to the manufacturers takes place [8].

To effectively close the supply chain loop, all essential elements must be involved, from suppliers to manufacturers, distribution centers and customers, collection and return centers, product and component recovery systems, and waste and polluting components disposal facilities. There have been significant advances in reverse flow research over the past few years, with much of it focusing on the movement of goods back into a supply chain [8]. In the traditional supply chain, the product flow moves from the supplier to the plant, and the finished items are sent out to the customers. With the introduction of reverse flows, end-of-life goods are being returned from end destinations (usually customers) back to the manufacturers, who either reintroduce them into the manufacturing system to be remanufactured or dispose of them responsibly in a waste treatment facility.

In the circular economy, remanufacturing plays a crucial role in maintaining the functionality and performance of products after their end-of-use/life. This is achieved by recovering the value of used products by reusing and recovering components and using them to produce new or like-new products [9]. Remanufacturing not only extends the useful life of products but also reduces the amount of waste materials entering the waste management system. Simultaneously, remanufacturing presents manufacturers worldwide with opportunities to make significant savings in materials and energy, minimize the amount of waste generated, and boost employment while bringing products of impeccable quality at lower cost into the market.

As industries increasingly adopt sustainable practices, the importance of efficient scheduling in remanufacturing processes has grown. Scheduling is an approach used to optimize manufacturing processes in order to enhance the performance of a given system or to get closer to its optimality in a short period of time (short-term schedule). Scheduling in remanufacturing is complex due to the variability in product conditions, the need for inventory management, and the integration of disassembly and assembly tasks. Therefore, proper scheduling and execution of remanufacturing operations such as disassembly and reassembly would make a significant impact in terms of achieving sustainability, cost savings, and resource conservation [10]. Since assembly and disassembly are key processes in remanufacturing, the concept of hybrid assembly and disassembly lines has gained significant attention due to the increasing need for efficient production systems that can adapt to both manufacturing and remanufacturing processes. Hybrid systems integrate assembly and disassembly tasks, allowing for a more flexible approach to production that can accommodate the complexities of modern manufacturing and sustainability goals. A hybrid assembly/disassembly line is characterized by its ability to perform both assembly and disassembly operations using shared workstations and resources. This integration is essential for optimizing productivity and resource utilization in remanufacturing environments.

Most studies in the technical literature on remanufacturing scheduling deal separately with assembly and disassembly scheduling problems. Only a few articles consider integrated assembly and disassembly and the possibility of using the same lines and equipment for both processes, such as the studies proposed by [11] and [12], which present hybrid systems for assembly and disassembly that can also be applied for remanufacturing processes. The integration of mixed disassembly and assembly operations on a single remanufacturing line assumes that the sequence of disassembly operations is precisely the inverse of the sequence of assembly operations.

Featuring dual workflows, this hybrid remanufacturing line is typical of a job-shop configuration or the confluence of two parallel flow shops, where one is dedicated to assembly with a direct flow and the other to disassembly with a reverse flow. To better understand this proposed mixed assembly/disassembly line model, Figure 1 provides a visual representation of its structure and components. In order to provide a clearer understanding of how the system operates, let us examine a hypothetical product consisting of three distinct components or subassemblies, denoted as A, B, and C. The product is sequentially assembled, first with part A, followed by part B, and concluding with part C, so replicating the workflow of an assembly line. On the other hand, when disassembling, it is presumed that components are taken out in the exact opposite order of their assembly. This means starting with C, then B, and lastly, A. To further illustrate this concept, consider the example of a computer hard drive. The assembly process involves attaching the printed circuit board (A) to the casing, followed by placing the platters (B) onto the spindle, and finally securing the top of the casing (C). Disassembly follows the reverse order, starting with removing the casing (C), then lifting the platters (B), and lastly detaching the printed circuit board (A). This practical example mirrors the sequential assembly and reverse disassembly process outlined in the model, highlighting its applicability to real-world scenarios. This hybrid line aims to effectively disassemble components and sub-assemblies from used items and eventually reassemble new remanufactured products.

Recent works have additionally focused on producing more realistic mathematical models by taking into account a range of parameters and constraints, including availability constraints, learning effects, deterioration effects, transportation, resource consumption, and sequence-dependent setup times [13]. Consequently, the literature has yet to investigate the integration of sequence-dependent setup time in the context of a mixed assembly/disassembly scheduling problem. In practice, sequence-dependent setup times are of significant importance when transitioning from one operation to another, as different setup times may be necessary to complete a specific sequence of assembly and disassembly operations. The growing need to take into account sequence-dependent setup times in order to achieve optimal and relevant scheduling is, therefore, motivating research efforts in this field.

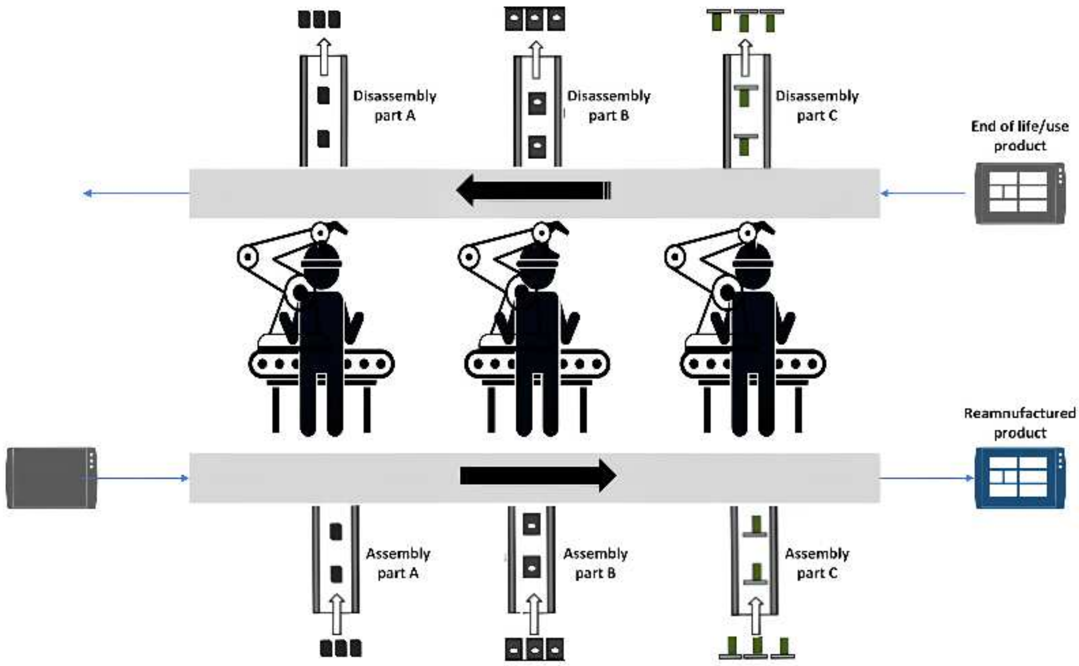

Figure 1 Schematic representation illustrating the setup of a combined assembly and disassembly line

The current study aims to create a resolution approach to remanufacturing operation scheduling that will maximize operational efficiency by successfully addressing the different aspects of this hybrid remanufacturing line. Our paper explores a relatively unexplored area of research, namely how to efficiently schedule two key remanufacturing processes, disassembly and assembly, to minimize the makespan while considering sequence-dependent setup time between assembly and disassembly operations. This research explores how remanufacturing processes affect circular economy principles and the quest for sustainability. At present, this particular approach to remanufacturing scheduling and the proposed mathematical formulation for its resolution address an important gap in the existing literature on remanufacturing scheduling, highlighting an innovative aspect of crucial importance for future research on this topic.

To resume, this paper presents two key contributions to the field of remanufacturing:

- This study introduces a hybrid line system for remanufacturing end-of-life/used products designed to optimize both assembly and disassembly processes.
- The research proposes a Mixed Integer Linear Programming (MILP) model to solve the scheduling problem of assembly and disassembly operations optimally while considering sequence-dependent setup time.
- The proposed MILP model offers an optimal solution for minimizing makespan and maximizing resource utilization on the hybrid line, contributing to more sustainable and cost-effective remanufacturing practices.

The remainder of this paper is presented methodically to present the various facets related to this remanufacturing scheduling problem. Section 2 presents a review of the available literature highlighting the importance of addressing this challenge. A detailed description of the problem studied, and its mathematical formulation is given in Section 3, aimed at providing optimal solutions for small and medium-sized instances of the problem, and in Section 4, we validate the proposed MILP model, providing test results that are also discussed. Finally, we present our conclusions in Section 5, summarizing our main contributions to the field of remanufacturing scheduling and their implications for both academic research and practical applications, as well as proposing potential directions for future exploration in this dynamic area.

2 Literature review

It is increasingly agreed that moving from the present linear industrial model to a circular economy is the key to achieving sustainable production and development, thereby creating a more sustainable and environmentally aware society. Transitioning to a circular economy involves rethinking traditional manufacturing processes and product life cycles to prioritize sustainable development. The challenge of achieving sustainability is, in general, a complicated process requiring numerous considerations, including technology and engineering, the environment, economics, human health and well-being, community aspirations, as well as public policy, procedures, and strategies [14,15]. This multifaceted approach ensures that sustainable practices are integrated at every industrial and societal development level.

Sustainable manufacturing as a whole relates to technical and organizational approaches that contribute to developing and implementing innovative manufacturing methods, designs, processes, and technologies to overcome the global scarcity of resources, reduce excessive environmental impact, and achieve environment-friendly product life cycles [16,17]. These innovations are crucial in driving the shift towards cleaner production practices. Sustainability in manufacturing encompasses all the stages of the product life cycle: design, pre-manufacturing, producing, usage, and post-utilization (reduce, reuse, recycle, recover, redesign, and remanufacture) [18,19]. By considering each stage of a product life cycle, manufacturers identify opportunities to minimize waste and enhance resource efficiency.

Furthermore, today's market is characterized by a growing demand for better-quality customized products, which can be obtained at the lowest cost in the shortest possible time. This production, which responds to the strong demand for new and customized products, results in enormous quantities of obsolete products that contain significant amounts of renewable resources. This paradox highlights the need for effective strategies to manage product obsolescence and resource recovery. Along with the increased environmental protection regulations [20], the increasing demand for environmentally friendly products [21] as well and the urge to take social responsibility [22], manufacturers are actively seeking new approaches to the way they operate their activities, which led to consider the return and the recycling of products at the end of their useful lives for reuse, recycling of materials, remanufacturing of products, reuse of component. Hence, the new kind of physical flow in the supply chains, known as reverse flows [23,24]. These reverse flows represent a significant shift in managing supply chains, prioritizing sustainable practices.

The most forward-thinking companies see the opportunities presented by this evolving landscape as a new revenue stream. For instance, item segregation or disassembly (i.e., the separation of a part or group of parts from an assembly using a reverse assembly flow) has been facilitated by the development of disassembly technologies and the creation of product designs that take specific consideration of disassembly requirements [25]. These developments lessen waste production and the carbon impact by simplifying recovering and reuse of valuable components of end-of-life/use goods.

Components can be repurposed, refurbished, or saved for later use after being disassembled. By decreasing waste and optimizing resource consumption, these strategies help to create an economy with greater circularity where resources are continuously cycled through the system. These initiatives also help the company's sustainability objectives and improve its reputation. As a result, businesses get a competitive edge in the market in addition to environmental benefits. To take full advantage of these prospects, businesses also need to deal with the challenges of scheduling these processes. The process of scheduling encompasses multiple layers of constraints, each of which requires special attention in order to guarantee effective operations and the most effective allocation of resources. Thus, enhancing profitability and operating efficiency, as well as lowering energy and resource consumption, all depend on effective scheduling in the remanufacturing sector [26]. As for assembly scheduling [27,28], there are numerous studies on disassembly scheduling issues, including [29,30], and [31]. However, integrating these two scheduling processes remains to be explored.

Given the complexity of remanufacturing activities, the topic of combined assembly and disassembly processes has obviously attracted some attention, as can be deduced from the works of [11,12,32,33]. Indeed, these research papers have laid the foundations for understanding an integrated production system's complexities and potential efficiencies. Although a fundamental framework exists for the application of mixed assembly and disassembly lines, significant gaps remain when it comes to addressing the inherent multifaceted challenges of scheduling the processes of these systems. Addressing these challenges requires innovative scheduling solutions that can adapt to the dynamic nature of hybrid production systems. An adjustment or setup operation often occurs in many real situations while moving between operations, hence the importance of considering setup times. Scheduling problems on the shop floor involving sequence-dependent setup times are encountered in numerous real-world situations, such as in the aerospace, printing, and semiconductor manufacturing industries [34,35].

To sum up, this hybrid assembly/disassembly line scheduling problem requires complex coordination of assembly and disassembly jobs, carefully considering the setup times associated with each type of job, especially given their sequence-dependent nature. The primary goal in solving this problem is developing an optimal scheduling plan for the jobs on the equipment with the aim of lowering the maximum completion time, or makespan. Reaching this goal is essential to improving remanufacturing businesses' overall efficiency.

3 Problem description and formulation

In the context of this remanufacturing setup, n jobs with known processing times are ready to be processed at time 0, across m workstations denoted as $\boldsymbol{M_1}, \boldsymbol{M_2}, \dots, \boldsymbol{M_m}$, with each job being treated on its assigned workstation, without interruption. These jobs have two possible flows:

- For the assembly process: a set of assembly jobs $\boldsymbol{E_A} = \{\boldsymbol{J_1}, \boldsymbol{J_2}, \dots, \boldsymbol{J_a}\}$ are processed following a direct flow from $\boldsymbol{M_1} \rightarrow \boldsymbol{M_2} \rightarrow \cdots \rightarrow \boldsymbol{M_m}$.
- For the disassembly process: a set of disassembly jobs $\boldsymbol{E_D} = \{\boldsymbol{J_{a+1}}, \boldsymbol{J_{a+2}}, \dots, \boldsymbol{J_n}\}$ are processed following a reverse flow, i.e., from $\boldsymbol{M_m} \rightarrow \boldsymbol{M_{m-1}} \rightarrow \cdots \rightarrow \boldsymbol{M_1}$.

This hybrid line scheduling problem is an NP-hard scenario that combines the constraints of sequence-dependent setup times with complicated assembly and disassembly processes. The term "setup time" describes the amount of time needed to prepare a resource for an operation, which may include activities like cleaning, modifying parameters, or switching out tools. The latter is a decisive factor in production efficiency, given that longer setup times can result in longer downtimes and lower productivity. Setup times are significant in real-world manufacturing and remanufacturing environments and can significantly impact the overall processing time or makespan.

In this framework, the setup time associated with a given job is not determined solely by the job itself; rather, it depends on the juxtaposition of this job with the one that precedes it. This dependency introduces a variable amount of transition time between successive jobs, which is intrinsically dependent on their sequence. For example, the time needed to configure the workstation to go from job 1 to job 2 may be very different from that needed to go from job 1 to job 5, regardless of the constancy of the workstation used. This additional dimension of variability considerably increases the complexity of this remanufacturing scheduling problem, requiring highly specialized scheduling strategies to optimize overall production efficiency and keep workstation downtime to a minimum. Also, one notable feature of this hybrid production line is the separable nature of these setup times, allowing the setup to begin as soon as a workstation becomes available (anticipatory setup). This characteristic significantly influences the efficiency of the scheduling process.

A mathematical formulation is presented to provide a precise and formal definition of the hybrid assembly/disassembly shop scheduling problem. This mixed-integer linear programming model includes an objective function that aims to minimize the makespan and a set of constraints that model the specific characteristics, constraints and requirements of this problem.

Let the following notations be defined:

Sets and Indices

- M: Set of all available workstations, $M = \{1, \dots, m\}$.
- J: Set of all jobs to be scheduled, $J = \{1, \dots, n\}$.
- P: set of positions, $P = \{1, \dots, p\}$, position of a job on the workstation.
- k: workstation index.
- j: job index.
- i: position index.
- $E_A = \{J_1, J_2, \dots, J_a\}$: set of assembly jobs.
- $E_D = \{J_{a+1}, J_{a+2}, \dots, J_n\}$: set of disassembly jobs.

Variables

- X_{kji}: Binary variable, equal to 1 if job j is assigned to workstation k at position i, 0 otherwise.
- $Y_{jj'}^{ki}$, $Y_{j'j}^{ki}$: Binary variables, equal to 1 if job $j \in E_A$ is followed by job $j' \in E_D$ on workstation k at positions $i, i+1$ or vice versa, and 0 otherwise.
- $t_{j,j'}$: Setup time between job j and job j′ when transitioning between assembly and disassembly operations on the same workstation k.
- p_{kj}: Processing time of job j on workstation k.
- s_{kj}: Start time of job j on workstation k.
- c_{kj}: Completion time of job j on workstation k.
- c_k: Completion time of all jobs on workstation k.
- C_{max}: Makespan.

3.1 Mixed-integer linear programming model

The objective function seeks to minimize the makespan, represented by equation (1), which is the completion time of the last job on the first or the last workstation:

$$Minimize\ C_{max} \quad (1)$$

The equations can be grouped into sets, and each group of equations corresponds to a type of constraint in the system. An explanation is given for each set of constraints:

Workstation and job assignment constraints:

$$\sum_{j \in n} X_{kji} = 1,\ \forall k \in M, i \in P \quad (2)$$

Equation (2) ensures that each position on every workstation is assigned to exactly one job from the set of all jobs. This constraint guarantees that no position on a workstation is left unassigned or assigned to more than one job.

$$\sum_{i \in p} X_{kji} = 1,\ \forall k \in M, j \in J \quad (3)$$

Equation (3) ensures that each job is assigned to exactly one position on each workstation and prevents a job from being processed in more than one position on the same workstation.

Assembly and disassembly sequencing constraints:

$$Y_{jj'}^{ki} = X_{kji} \times X_{kj'(i+1)},\ \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \quad (4)$$

$$Y_{j'j}^{ki} = X_{kj'i} \times X_{kj(i+1)},\ \forall k \in M, i \in P - \{p\}, j \in E_A \quad (5)$$

Constraints (4) and (5) define the order of assembly and disassembly jobs. They ensure that if an assembly job j is followed by a disassembly job j′ on workstation k at position i and i+1, or vice versa, this order is correctly reflected in the variables $Y_{jj'}^{ki}$ and $Y_{j'j}^{ki}$.

Binary variable constraints for sequencing:

$$Y_{jj'}^{ki} \leq X_{kji}, \; \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{6}$$

$$Y_{jj'}^{ki} \leq X_{kj'(i+1)}, \; \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{7}$$

$$Y_{jj'}^{ki} \geq \left(X_{kji} + X_{kj'(i+1)}\right) - 1, \qquad \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{8}$$

$$Y_{j'j}^{ki} \leq X_{kj'i}, \qquad \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{9}$$

$$Y_{j'j}^{ki} \leq X_{kj(i+1)}, \qquad \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{10}$$

$$Y_{j'j}^{ki} \geq \left(X_{kj'i} + X_{kj(i+1)}\right) - 1, \qquad \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{11}$$

Equations (6) to (11) link the binary variables $X_{kji}, Y_{jj'}^{ki}$, and $Y_{j'j}^{ki}$. These constraints ensure that the sequencing binary variables Y are set to 1 if and only if both corresponding jobs j and j′ are assigned to consecutive positions i and i+1 on the same workstation k.

Start time constraints for assembly and disassembly jobs:

$$s_{1j} \leq M \cdot \left(1 - X_{1,j,1}\right), \qquad \forall j \in E_A \tag{12}$$

Constraint (12) sets a large enough start time for the first job in the assembly jobs set if it isn't assigned to the first position on the first workstation.

$$s_{mj} \leq M \cdot \left(1 - X_{m,j,1}\right), \qquad \forall j \in E_D \tag{13}$$

Constraint (13) is similar to the previous equation but for disassembly jobs. It sets the start time for disassembly jobs on the last workstation m.

Sequencing and setup-time constraints:

$$s_{kj} + p_{kj} + t_{j,j'} \leq s_{kj'} + M \cdot \left(1 - Y_{jj'}^{ki}\right), \qquad \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{14}$$

$$s_{kj'} + p_{kj'} + t_{j',j} \leq s_{kj} + M \cdot \left(1 - Y_{j'j}^{ki}\right), \qquad \forall k \in M, i \in P - \{p\}, j \in E_A, j' \in E_D \tag{15}$$

Equations (14) and (15) ensure the correct sequencing of jobs, including the sequence-dependent setup time required between them. These constraints define the relationship between start times, processing times, and setup times, accounting for the order of assembly and disassembly jobs.

Continuity of jobs constraints:

$$s_{kj} + p_{kj} \leq c_{kj}, \qquad \forall k \in M, j \in E_A \tag{16}$$

$$c_{kj} \leq s_{(k+1)j}, \qquad \forall k \in M - \{m\}, j \in E_A \tag{17}$$

$$s_{kj} + p_{kj} \leq c_{kj}, \qquad \forall k \in M, j \in E_D \tag{18}$$

$$c_{kj} \leq s_{(k-1)j}, \qquad \forall k \in M - \{1\}, j \in E_D \tag{19}$$

Since we have one direct and one reverse flow, constraints (16) to (19) ensure that for assembly jobs, the completion time on one workstation is before the start time on the next one, and for disassembly jobs, the completion time on one workstation is before the start time on the previous one.

Positional continuity constraints:

$$s_{kj} + M \cdot \left(1 - X_{kj(i+1)}\right) \geq p_{kj'} + s_{kj'} - M \cdot \left(1 - X_{kji'}\right), \qquad \forall j, j' \in J, k \in M, i \in P - \{p\} \tag{20}$$

Considering the processing times, constraint (20) ensures the continuity of job positions on each workstation.

Maximum completion time constraints:

$$c_k = max\{c_{kj}\}, \qquad \forall k \in M, j \in J \tag{21}$$

$$C_{\max} = max\{c_k\}, \forall k \in M \tag{22}$$

Equation (21) calculates the completion time of all jobs on each workstation k as the maximum completion time of individual jobs. Equation (22) defines the makespan as the maximum of these completion times across all workstations.

4 Results and discussion

To validate the efficacy of the proposed model, we conducted extensive computational experiments across various small and medium-sized instances with samples of processing times with a *U*(1.99) and setup times with a *U*(1.30) distribution in order to reflect the actual operating conditions in our test cases, giving a more realistic assessment of this scheduling challenge. The mixed-integer linear programming model developed for this study was solved using IBM ILOG CPLEX solver. This software is renowned for its efficient handling of linear programming, mixed-integer programming, and many other complex computational applications. The following is a sample instance that was solved effectively by our MILP model:

Consider, for instance, a workshop featuring a hybrid production line equipped with five workstations, denoted as $M_1, M_2, \ldots, M_5$. Three assembly jobs designated $J_1, J_2, and\ J_3$ are handled alongside three disassembly jobs $J_4, J_5, and\ J_6$. While the assembly operations traverse the line in a forward sequence from M_1, M_2, ...through M5, the disassembly operations undergo processing in reverse order, i.e., from M_5 to M_1.

An illustrative instance is presented to demonstrate the model's application, followed by a detailed solution analysis and a Gantt chart visualization. Table 1 tabulates the processing times for each job's operations, whereas Table 2 details the sequence-dependent setup times required when transitioning between assembly and disassembly jobs on the same workstation.

Our MILP model uses strategic sequencing of the operations across the workstations to mitigate lengthy setup times, which is essential to minimizing the overall production time (makespan). The Gantt chart (refer to Figure 2) provides a visual representation of the optimal schedule generated by the MILP model of the instance given as an example. Each row corresponds to a workstation, and each colored block denotes a job's execution on that workstation. The length of the block signifies the processing time, while any gaps between blocks indicate idle periods and the red segments represent the setup phase. To provide a comprehensive understanding of the schedule, let us examine the Gantt chart step-by-step.

Table 1 Processing times

	M_1	M_2	M_3	M_4	M_5
J_1	**51**	**47**	**18**	**95**	**35**
J_2	**59**	**62**	**27**	**81**	**26**
J_3	**87**	**56**	**75**	**13**	**36**
J_4	**75**	**91**	**54**	**73**	**51**
J_5	**52**	**37**	**29**	**13**	**63**
J_6	**20**	**64**	**58**	**20**	**48**

Table 2 Setup times

	M_1	M_2	M_3	M_4	M_5	M_6
J_1	**-**	**-**	**-**	**16**	**5**	**1**
J_2	**-**	**-**	**-**	**4**	**11**	**16**
J_3	**-**	**-**	**-**	**5**	**4**	**4**
J_4	**14**	**5**	**15**	**-**	**-**	**-**
J_5	**11**	**17**	**14**	**-**	**-**	**-**
J_6	**19**	**4**	**6**	**-**	**-**	**-**

Beginning with Machine 1, we observe that it initiates the assembly process by processing Job 1, followed by Job 2, and then 3. Once Job 3 is complete, the machine transitions to handle disassembly jobs after a setup operation, starting with Job 4, then Job 5, and lastly, Job 6. The red segments interspersed between these jobs represent the setup-time required when switching between assembly and disassembly operations. Moving on to Machine 5, it commences with Job 4 at time 0, succeeded by Job 5 and then 6. Subsequently, after the setup operation, it processes Job 2 from the assembly set, followed by Job 1, and finally, Job 3. The pattern continues similarly across the remaining machines, with each machine handling a mix of assembly and disassembly jobs based on their designated flow and the optimized schedule achieved by the MILP model.

The chart visually depicts the makespan, which is the total time required to complete all jobs, as 465.0 units. This detailed walkthrough of the Gantt chart underscores the model's ability to efficiently allocate and sequence jobs while considering setup time constraints and the hybrid nature of the assembly/disassembly line. Crucially, the chart showcases the model's strategic sequencing to minimize makespan. For example, on workstation 5, Job 5's operation precedes Job 6's, yet this order is reversed on workstation 4. This deliberate reordering stems from the varying setup times between different job combinations. By prioritizing the sequence with the shortest setup, the model effectively reduces overall production time. Similar strategic sequencing is evident for Jobs 1 and 2 on workstations 2 and 3.

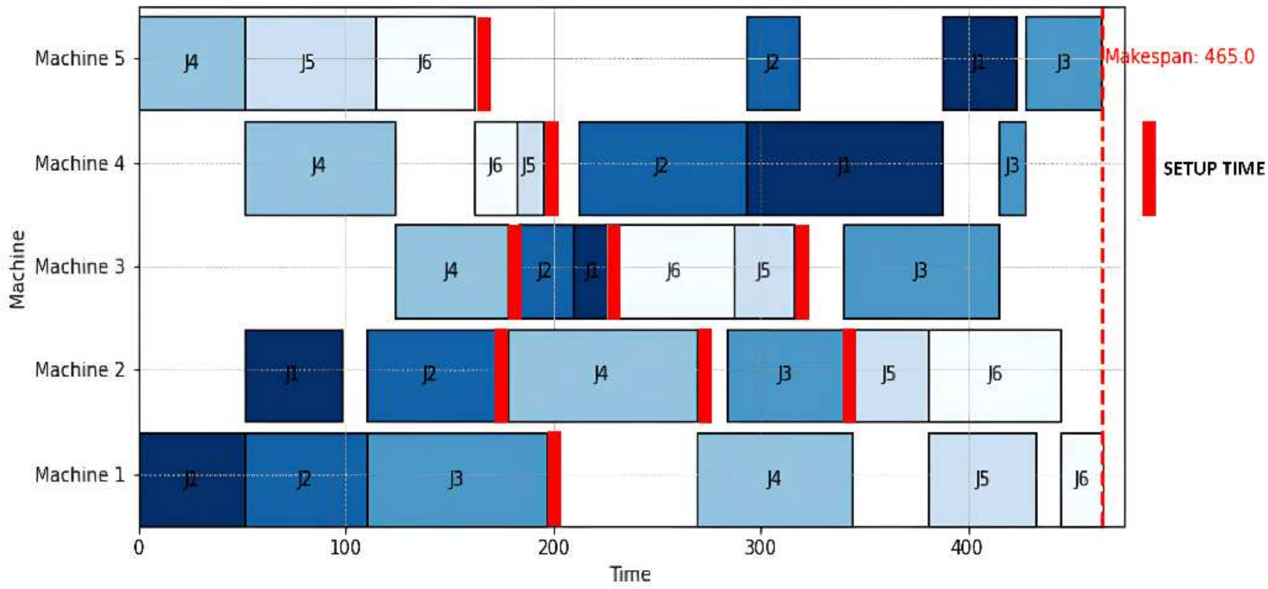

Figure 2 Gantt chart of the sample instance

This purposeful reordering is motivated by the different requirements of subsequent jobs, leading the model to seek out the optimal sequence that requires the shortest applicable setup time. These sequencing decisions underline the MILP's ability to take careful account of setup times between jobs. While the MILP model proved its effectiveness in solving the problem faced by small and some medium-sized instances, it encounters significant computational limitations as the size of the problem increases. The complexities of larger instances lead to an exponential increase in computational time, thus preventing the MILP from providing timely solutions for large-scale applications. The execution of the MILP for small and medium-sized is carried out quickly, and the results are available immediately. When running the mathematical model for larger instances, it took, in many cases, over three hours to successfully run the model with 20 jobs/3 workstations instances and over 12 hours to execute the problem with 20 jobs/5 workstations using the model proposed. So, the bigger the instance, the longer it takes to solve the problem.

5 Conclusion and perspectives

Efficient scheduling in remanufacturing is essential for maximizing resource allocation and improving efficiency, and this study contributes to the field of remanufacturing optimization by developing and validating a mixed-integer linear programming (MILP) model for scheduling hybrid assembly/disassembly lines with sequence-dependent setup times, an aspect that has not been adequately addressed in the existing literature. This model offers an effective strategy for optimizing small and medium-sized instances of this NP-hard problem, potentially leading to improved resource allocation, reduced costs, and enhanced sustainability in remanufacturing facilities. The MILP model's efficacy was demonstrated through computational experiments showcasing its ability to generate optimal schedules. The Gantt chart visualization further highlighted the model's strategic sequencing of jobs to minimize makespan and effectively manage the complexities of the assembly disassembly hybrid line. Nevertheless, the research also acknowledges the computational limitations of the MILP model when dealing with instances of significant scale. This limitation highlights the need for further exploration into advanced optimization techniques and algorithms that can efficiently handle the complexities of larger remanufacturing systems.

Future work could focus on developing and evaluating advanced algorithms that can efficiently tackle large-scale hybrid assembly/disassembly scheduling problems. These algorithms could incorporate techniques like decomposition, relaxation, or machine learning to enhance computational performance. The current model could be extended to include additional real-world constraints, such as machine breakdowns, uncertain processing times, parts transportation, or multiple product types. Such extensions would further enhance the model's applicability and practicality. Furthermore, exploring the integration of this scheduling model with Industry 4.0 technologies, such as real-time data collection and analysis, could enable dynamic scheduling and further optimize production processes. By taking these directions, a more holistic grasp of remanufacturing systems can be achieved, which is of growing relevance in the context of resource scarcity and the global drive towards more environmentally friendly manufacturing practices. As such, this paper serves as a solution to a current challenge and serves as a foundation for further research into the evolving landscape of remanufacturing optimization.

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