Pricing-Driven Optimization of Lot-Sizing and Scheduling in Hybrid Manufacturing-Remanufacturing Systems

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Abstract— **The transition towards sustainable production models has intensified interest in hybrid manufacturing and remanufacturing systems, which play a crucial role in the circular economy. These systems integrate new production with the refurbishment of used products, presenting unique operational challenges. This paper examines the integration of pricing, scheduling, and lot-sizing in modern industrial operations, with a focus on hybrid manufacturing and remanufacturing systems. The study aims to optimize these interdependent elements by addressing two key objectives: maximizing profitability through pricing strategies and minimizing makespan in production scheduling. To tackle this complex problem, a multi-objective heuristic algorithm is designed to explore and compare different strategies. The proposed algorithm identifies optimal trade-offs between economic performance and operational efficiency, ensuring applicability in real-world hybrid production environments.**

I. INTRODUCTION

The shift toward circular economy models has become imperative for many industries, driven by growing global concerns over resource depletion and environmental sustainability. A circular economy emphasizes reducing waste, reusing products, and recycling materials, minimizing the ecological footprint of industrial operations while maintaining economic viability. In this framework, remanufacturing—restoring end-of-life (EOL) or end-of-use (EOU) products to like-new condition plays a pivotal role. It reduces the need for extracting new raw materials, energy consumption, and greenhouse gas emissions compared to traditional manufacturing processes [1]. However, remanufacturing significantly contributes to sustainability, but cannot fully replace new production. Industries must continue developing new products to meet technological advancements, evolving consumer needs, and regulatory requirements. The challenge lies in integrating remanufacturing into traditional production systems in a hybrid approach, combining new product manufacturing with refurbishment processes to balance economic competitiveness and ecological responsibility [2].

Hybrid manufacturing and remanufacturing systems require efficient planning of material flows, lot-sizing, and production scheduling to accommodate newly manufactured and refurbished products. Unlike traditional linear production models, hybrid systems involve complex trade-offs between production efficiency, cost-effectiveness, and environmental objectives. One of the key challenges in hybrid production lies in the interdependence between dynamic pricing, demand fluctuations, and production planning. Pricing strategies influence consumer demand for new and remanufactured products, affecting lot-sizing decisions and scheduling processes. Traditionally, marketing departments manage pricing decisions while manufacturing teams handle production planning separately. Integrating pricing and production planning within a unified framework becomes essential in developing a build-to-order model, where production aligns closely with demand. Optimizing pricing for new and remanufactured products allows companies to proactively adjust demand, minimize overstocking risks, and ensure sustainable resource utilization.

While lot-sizing, scheduling, and pricing optimization have been widely studied individually, few studies have explored their integration within hybrid production systems. The increasing prominence of these systems reflects broader industrial trends toward sustainability and resource efficiency. Policymakers, particularly in the European Union, have emphasized the importance of circular economy principles [3], encouraging businesses to adopt models that extend product life cycles and reduce raw material consumption.

This paper contributes to the growing body of research by exploring the simultaneous optimization of pricing, lot sizing, and scheduling in hybrid systems. It proposes a multi-objective heuristic algorithm to balance the dual goals of maximizing profit through strategic pricing and minimizing makespan in production processes. The model is applied to a scheduling environment with multiple machine configurations. Product flow through a series of stages, including testing, disassembly, reprocessing, and reassembly workstations, each dedicated to manufacturing or remanufacturing operations. By addressing these interdependent challenges, the study aims to provide a holistic solution that enhances decision-making in hybrid production systems, offering practical benefits for industries seeking to align their operations with the principles of the circular economy.

The remainder of this paper is organized as follows: In the section II, we review the relevant literature to position our research and highlight our contributions. Section III presents a detailed description of the problem. In Section IV, we describe our solution approach, based on a multi-objective heuristic, which we test to determine a trade-off between optimal pricing and scheduling decisions for new and remanufactured products. We discuss the results and insights gained from these experiments. Finally, Section V concludes the paper and outlines potential future research directions.

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II. RELATED WORKS

In response to the growing demand for sustainable industrial practices, adopting remanufacturing strategies aligns with environmental goals and presents an opportunity to enhance profitability through resource efficiency. Several studies have explored the potential of remanufacturing systems in fostering sustainability while maintaining economic viability [4], [5]. However, despite extensive research on specific operational aspects such as lot-sizing, scheduling, and pricing, these decisions are often studied separately, despite their inherent interdependencies. Most research on hybrid production systems has primarily focused on integrating scheduling and lot-sizing to determine optimal production quantities and allocate resources and time slots to manufacturing tasks. These works emphasize the importance of coordinating these two decisions to enhance efficiency and reduce costs in environments that integrate remanufacturing [6].

Similarly, pricing and lot-sizing have been studied together, particularly in market-driven production systems. For instance, Doh et al. [7] study the dynamic interaction between pricing and lot-sizing in short-life-cycle products, showing that consumer perception of remanufactured goods and price discounts strongly influence production decisions. Likewise, Zouadi et al. [8] explore pricing and lot-sizing under one-way substitution between new and remanufactured products, highlighting the challenges of synchronizing production planning under uncertain demand and product returns. Additionally, Kilic et al. [9] examine the effect of market segmentation on pricing and lot-sizing, demonstrating that pricing strategies tailored to different consumer segments can optimize profitability and demand satisfaction.

Various optimisation approaches have been proposed to address these complex decision-making problems, ranging from exact methods to heuristics and metaheuristics [10]. For example, some studies apply genetic algorithms to optimize production planning [11]. In contrast, Baki et al. [12] develop heuristic models to minimize production, setup, and storage costs in remanufacturing environments using mixed-integer linear programming (MILP).

The main gap in the literature lies in the limited research on the simultaneous integration of pricing, scheduling, and lot-sizing decisions. It is worth considering the three decision levels, as pricing directly influences demand, which in turn impacts lot-sizing and scheduling strategies. The work of Nouinou et al. [13] emphasizes the importance of integrating these decisions, acknowledging that pricing influences demand levels, which in turn determine production quantities. Additionally, Steeneck et al. [14] argue that aligning pricing strategies with scheduling is crucial to ensure cost-effective and sustainable remanufacturing processes.

While previous research has examined individual interactions between pricing, lot-sizing, and scheduling, our work simultaneously addresses these three decision levels within a hybrid manufacturing and remanufacturing environment composed of four interconnected subsystems: (1) testing workstations, (2) disassembly workstations, (3) a flexible job shop for reprocessing, and (4) reassembly workstations.

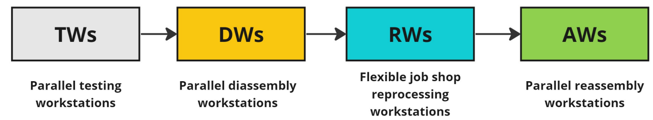


Fig. 1. Configuration of hybrid manufacturing and remanufacturing system

A key challenge in such complex systems is finding the right balance between the pricing of new and remanufactured products, the resulting demand for each, and the feasibility of scheduling within the overall system. Setting prices too low can significantly increase demand, complicating scheduling, while high prices may reduce profitability and result in underutilization of production capacity. Therefore, our study adopts a multi-objective optimization perspective, aiming to maximize profit through strategic pricing and minimize makespan, ensuring that production schedules remain manageable. The solution approach illustrates how varying pricing can influence profitability and operational factors, ensuring sustainable and well-coordinated manufacturing and remanufacturing processes.

III. PROBLEM DESCRIPTION

The system considered in this study operates as a hybrid production system, comprising two distinct but interconnected processes: one dedicated to remanufacturing end-of-life (EOL)/end-of-production (EOF) products, and the other to manufacturing new products. As illustrated in Figure 1, this system consists of four sequential subsystems: testing workstations (TWs), disassembly workstations (DWs), reprocessing workstations (RWs), and assembly workstations (AWs). In remanufacturing, the EOL/EOF first undergoes testing (TWs) to determine its quality. Based on this evaluation, they are disassembled (DWs) into a set of components; higher-quality products require less disassembly, whereas lower-quality ones must be broken down further. These components then move to reprocessing workstations (RWs), where they undergo repair, cleaning, and painting operations to restore them to a functional state. Finally, the restored components are reassembled (AWs) into remanufactured products that meet the same high-quality standards as new ones. Meanwhile, new components are assembled directly at AWs to create new products in the manufacturing process and then tested at TWs to ensure quality. Figure 2 represents the two processes within the hybrid system.

This hybrid manufacturing and remanufacturing system requires three fundamental decision-making from the manufacturer perspective: (1) optimizing job sequencing and machine assignments to minimize the total completion time (makespan), (2) determining the optimal quantities of manufactured and remanufactured products, and (3) establishing a profitable pricing strategy for both product types.

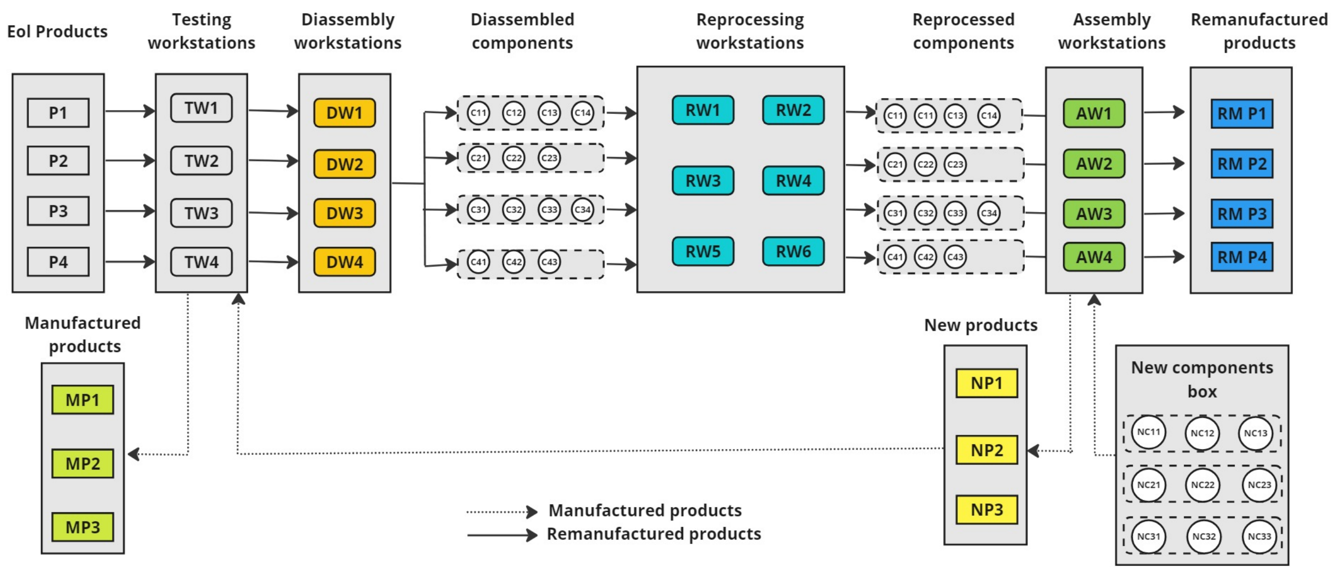


Fig. 2. Hybrid Manufacturing and Remanufacturing Process

At the beginning of a finite planning period, the manufacturer sets prices for new and remanufactured products, which directly influences customer demand. To define and address this problem, several essential parameters must be considered:

- Pricing and demand: The set prices for manufactured and remanufactured products determine the demand for each type of product.
- Processing times: These include testing times for both product types, disassembly times for remanufactured products, operation-specific processing times at reprocessing workstations, and assembly times.
- Costs: Manufacturing cost per unit and remanufacturing cost per unit, depending on the quality assessed during testing.

The problem requires solving multiple scheduling and assignment decisions to ensure efficient production flow :

- Determining the maximum completion time for manufacturing and remanufacturing operations.
- Scheduling the start times for testing of manufactured and remanufactured products, disassembly of remanufactured products, reprocessing of disassembled components, and assembly of both manufactured and remanufactured products.
- Assigning manufactured and remanufactured products to appropriate testing workstations.
- Assigning remanufactured products to disassembly workstations.
- Distributing components for processing at the correct reprocessing workstations.
- Assigning final products to the suitable assembly workstations.

To ensure the feasibility of the manufacturing and remanufacturing process, several constraints must be satisfied :

- Disassembly of remanufactured products cannot begin until testing is completed.
- Assembly of remanufactured products must wait until all required components are reprocessed.
- For newly manufactured products, testing can only occur after assembly is complete.

The problem considers two objectives:

- Profit maximization: The profit is determined by the difference between the price of manufactured and remanufactured products and their respective manufacturing and remanufacturing costs. The objective is to achieve the highest possible sales volume without incurring excessive operational expenses.
- Makespan minimization; Reducing the total completion time of all operations.

In the work of Zhang et al. [15], the problem studied exclusively concerns a remanufacturing system. Although their approach is multi-objective, it does not consider price integration. Furthermore, although the proposed mathematical model accurately describes the problem, it is not linear and cannot be applied directly to achieve an efficient solution. Given the increased complexity of our problem and to better structure our approach, we have chosen a problem description that facilitates the application of our heuristic method. In the following section, we present our adapted solution approach.

IV. SOLUTION APPROACH AND EXPERIMENTAL STUDY

This section presents our heuristic approach to addressing the problem, making informed decisions, and achieving the objectives within the constraints mentioned above. We developed a three-decision-level approach that constructs a solution considering pricing and demand selection, worksta-

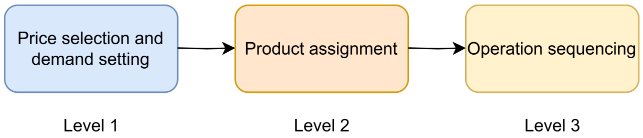


Fig. 3. Three-decision-level approach

tion assignment and selection, and the operation sequence (Figure 3).

A. *First-level for pricing and demand selection*

We will use the notation 0 to represent products to be manufactured and 1 for products to be remanufactured. The first level represents a solution to the price selection. Here, we will assign a random number from the continuous uniform distribution. We consider a set of prices for each product type. We assign a random price to each product, whether it is remanufactured or manufactured. Based on these prices, we can determine the demand. For instance, for the manufactured product, we have three proposed prices (3.9, 8.5, and 9.1), and for each price, we can assess the corresponding demand, given that demand decreases as prices increase.

B. *Second-level for workstation assignment and selection*

This level aims to establish the assignment of workstations and the selection of various types, such as TWs, DWs, RWs, and AWs, for remanufactured products, as well as AWs and TWs for manufactured products. As described in the problem description section, TWs, DWs, and AWs are parallel and identical machines, implying that EOL or EOU products can be assigned to any workstation with the same processing time. However, for reprocessing, we consider a Flexible Job Shop (FJS), where one reprocessing operation can be carried out on one or more reprocessing workstations with varying reprocessing times.

For each available workstation, we randomly assign a real number within the range $[0; 10]$. Subsequently, we select the maximum real number for each operation. For instance, in the example illustrated in Figure 4, we have three products: two remanufactured (11 and 12) and one manufactured (01). Each product will be allocated to the workstation with the highest assigned number.

In the reprocessing steps, each component can undergo various operations, and each operation can be executed on different processing workstations among all available options. For example, in Figure 5, we have a remanufactured product 1 that will be disassembled into three components. Each component has a certain number of operations that can be executed in one or more reprocessing workstations among the three. We randomly assign a real number to each operation. After that, we will assign the job to the operation with the highest number.

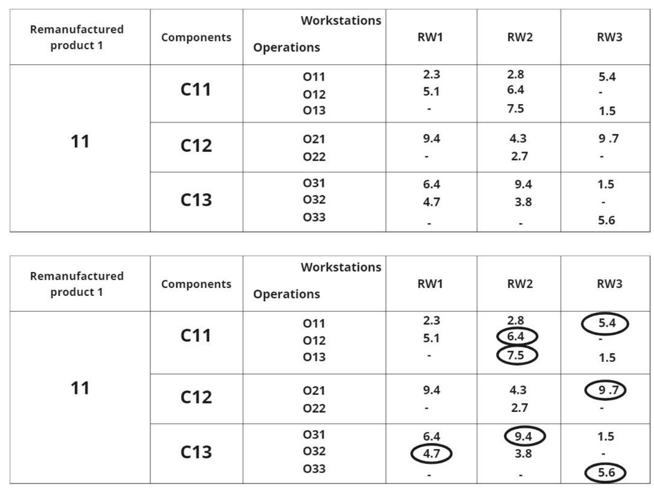
C. *Third-level for operations sequence:*

At this level, we sort all operations, starting from testing, disassembly, reprocessing, and assembly for remanufactured

	TW1	TW2	DW1	DW2	AW1	AW2
11	0.98	9.1	5.3	8.4	2.7	6.1
12	0.91	3.56	4.2	0.56	6.5	1.7
01	7.98	2.41	-	-	0.53	2.99

	TW1	TW2	DW1	DW2	AW1	AW2
11	0.98	9.1	5.3	8.4	2.7	6.1
12	0.91	3.56	4.2	0.56	6.5	1.7
01	7.98	2.41	-	-	0.53	2.99

Fig. 4. Example of workstation assignment



Remanufactured product 1	Components	Workstations / Operations	RW1	RW2	RW3
11	C11	O11	2.3	2.8	5.4
		O12	5.1	6.4	-
		O13	-	7.5	1.5
	C12	O21	9.4	4.3	9.7
		O22	-	2.7	-
	C13	O31	6.4	9.4	1.5
		O32	4.7	3.8	-
		O33	-	-	5.6

Remanufactured product 1	Components	Workstations / Operations	RW1	RW2	RW3
11	C11	O11	2.3	2.8	5.4
		O12	5.1	6.4	-
		O13	-	7.5	1.5
	C12	O21	9.4	4.3	9.7
		O22	-	2.7	-
	C13	O31	6.4	9.4	1.5
		O32	4.7	3.8	-
		O33	-	-	5.6

Fig. 5. Example of reprocessing assignment and selection

products, as well as assembly and testing for manufactured ones. However, before ordering the operations for all the processes, we start with the reprocessing operations for the remanufactured product. Figure 6 shows that the remanufactured product 1 will be disassembled into 3 components. Each component is following a processing route with a number of operations. These operations are reprocessed in an available adequate RW.

Due to the differing paths of manufacturing and remanufacturing operations, we have adopted the following strategy: testing of manufactured products occurred after testing of remanufactured products.

Given the following prices for remanufactured products as shown in Table I, we generated the corresponding demand using a linear function. We estimated the remanufacturing cost to be 40% of the remanufactured product price.

We consider a similar set of prices for manufactured products as shown in Table II, and we determined the demand using the same function.

Based on this data, the program selected a price of 42 for the remanufactured product and 40 for the manufactured

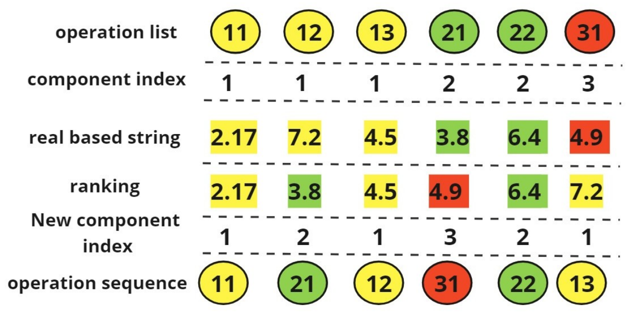


Fig. 6. Operations of reprocessing sequence within one remanufactured product

TABLE I
PRICES, DEMAND, AND COSTS FOR REMANUFACTURED PRODUCTS

Price	Demand	Cost
32	4	12.8
42	3	16.8
50	2	20

product. This results in a demand of 3 units for both remanufactured and manufactured products.

Subsequently, the program provided a detailed assignment and scheduling of these products, summarized in the Gantt diagrams shown in Figures 7, 8, 9, and 10.

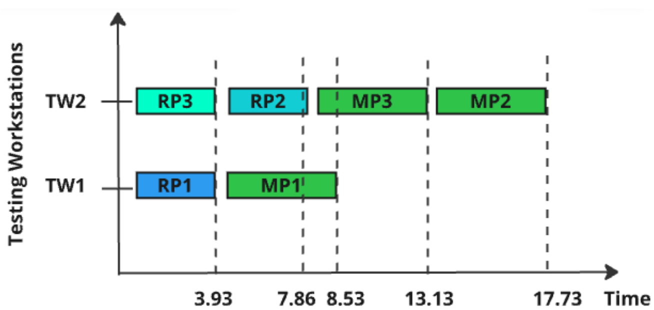


Fig. 7. Assignment and scheduling for testing

For example, in Figure 7, Remanufactured Product 1 and Manufactured Product 1 are allocated to Testing Workstation 1, while Remanufactured Products 2 and 3, along with Manufactured Products 2 and 3, are assigned to Testing Workstation 2.

Additionally, the program provides detailed information about both manufactured and remanufactured products. The durations for these processes are generated using a uniform distribution and account for various factors, including the quality of the remanufactured products after testing. Table III details the durations required for the different steps involved in manufacturing and remanufacturing the products.

Additionally, the diagram in Figure 9 displays the distribution of components across reprocessing workstations based on their operation type. For example, we consider that Cleaning is performed in Reprocessing Workstations 1 and 2.

TABLE II
PRICES, DEMAND, AND COSTS FOR MANUFACTURED PRODUCTS

Price	Demand	Cost
30	4	18
40	3	24
50	2	30

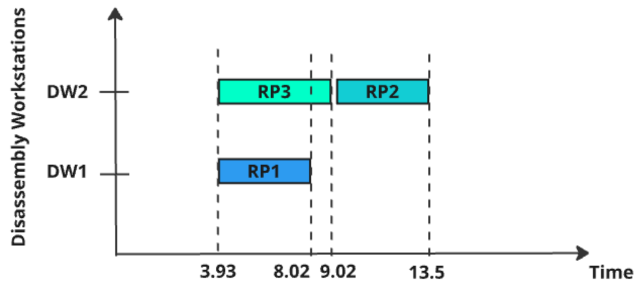


Fig. 8. Assignment and scheduling for disassembly

TABLE III
DURATIONS FOR MANUFACTURED, REMANUFACTURED, AND REPROCESSING OPERATIONS

Operations	Operation	Duration (hours)
Manufacturing	Testing	4.6
	Assembly	5.80
Remanufacturing	Testing (Reman)	3.93
	Disassembly (RP1)	4.09
	Disassembly (RP2)	5.09
	Disassembly (RP3)	4.48
	Assembly (RP1)	2.7
	Assembly (RP2)	1.38
	Assembly (RP3)	3.01
Reprocessing	Cleaning	3.1
	Inspection	1.9
	Repair	2.5
	Reconditioning	2

Inspection is conducted in Reprocessing Workstations 3 and 4. Repair is carried out in Reprocessing Workstations 5 and 6. Reconditioning takes place in Reprocessing Workstations 7 and 8. Finally, 10 shows that the last remanufactured product exits the Assembly Workstation at time 23.4, indicating that the total makespan is 23.4. The corresponding profit is 123.6.

Based on the same duration and cost data, we are interested in running tests to analyze the impact of price variations

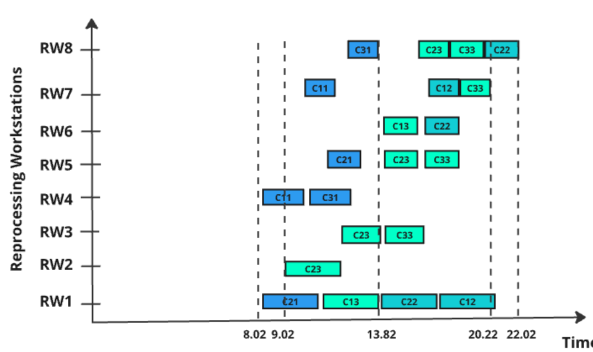


Fig. 9. Assignment and scheduling for reprocessing

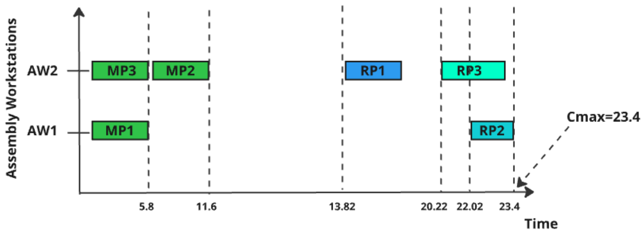


Fig. 10. Assignment and scheduling for assembly

on demand, scheduling efficiency, and overall profitability in a hybrid manufacturing and remanufacturing system. Since pricing directly influences demand, it affects the production lots and scheduling decisions, determining the makepan and total profit.

TABLE IV
VARIATION OF PRICES AND DEMANDS WITH CORRESPONDING MAKESPAN AND TOTAL PROFIT

Test	M-Price	Demand	R-Price	Demand	Makespan	Profit
1	50	2	40	3	53.78	157.8
2	60	3	30	5	60.32	189.4
3	40	4	50	2	49.21	146.7
4	70	1	30	6	65.87	204.5
5	50	3	40	4	55.43	171.2

As shown in Table IV, the results show that higher prices typically reduce demand but can increase profit margins. Conversely, lower prices increase demand, which in turn extends the makespan and potentially complicates the scheduling process. For instance, Test 4, where the manufactured product price is the highest and demand is the lowest, yields the longest makespan but the highest profit. In contrast, Test 3, where manufactured products are priced lower, sees a higher demand but a shorter makespan and lower total profit.

This heuristic approach generates a solution based on randomly assigned values, thereby enabling the generation of multiple distinct solutions. These solutions can subsequently be used to initialize the population of a multi-objective genetic algorithm. The proposed solution representation supports the application of genetic operators such as crossover and mutation. The design and implementation of the corresponding metaheuristic will be the subject of future research.

V. CONCLUSIONS

This research was conducted within the framework of the circular economy, focusing on a hybrid manufacturing and remanufacturing system. We developed an integrated strategy that combines pricing, lot sizing, and scheduling to minimize the makespan and maximize profit. To address this problem, we proposed a heuristic capable of generating feasible solutions. Our future work will focus on developing a mathematical model that enables more structured problem resolution based on previous research on simple systems considering manufacturing or remanufacturing. Additionally, we aim to refine our heuristic and use it as a chromosome encoding method within a multi-objective genetic algorithm. Due to the lack of comparable studies, we have not been able to benchmark our results against similar problems.

The tests we conducted were particularly valuable in analyzing the impact of pricing on demand, scheduling efficiency, and overall profitability. They highlighted the trade-offs between production time and financial performance, emphasizing the importance of an optimized pricing strategy. These insights will guide future developments and refine decision-making models for hybrid systems.

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