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# A hybrid architecture for a Reconfigurable Cellular Remanufacturing System

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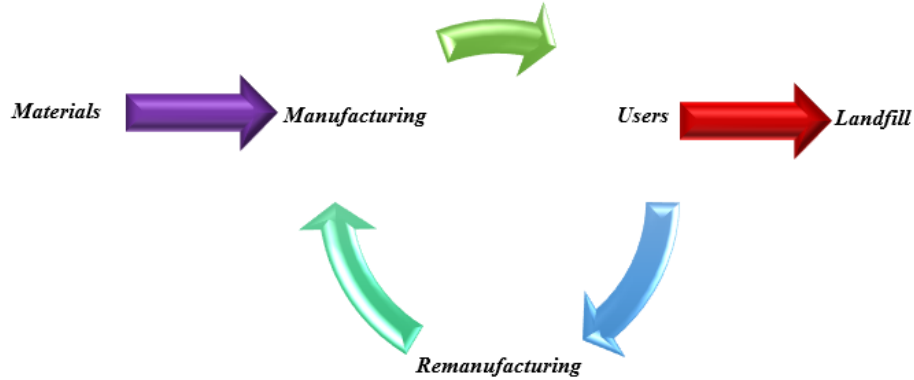
**Abstract.** Remanufacturing is a practice that postpones the product ‘end-of-life,’ returning the properties or features of a new product to a used product. This type of process represents an efficient circular economy strategy to extend product life, reducing its footprint. However, remanufacturing systems must overcome different challenges related to uncertainty and its impact on efficiency. In this sense, this study exposes a hybrid remanufacturing-manufacturing architecture with embedded features from cellular and reconfigurable manufacturing systems. The architecture was synthesized in a Mixed Integer Non-Linear optimization model, which defines the remanufacturing system configuring the cells and product families, balancing the workloads, establishing the scheduling sequence and quantifying the reconfigurability cost. The result is a self-adaptative system that maintains a continuous production rate by managing its capacity.

**Keywords:** Remanufacturing · Reconfigurability · Cellular manufacturing.

## 1 Introduction

Circular Economy (CE) has become a feasible alternative to face environmental challenges and provide sustainable solutions. The application of CE strategies or 9 R’s framework, which includes refuse, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover energy [5] promotes technical and natural loops [8]. In this sense, remanufacturing takes significant importance closing the loop [6] (see figure 1), in which products could recover its conditions as a new product and be returned to users [13], but with a reduced ecological footprint [6] and price [13]. Remanufacturing has other advantages as savings in labor, material, and energy costs, shorter production lead times, new market and product development opportunities, and even an improvement in the firm image by exposing a positive socially concerned image [4].

Remanufacturing has significant advantages for the Original Equipment Manufacturers (OEMs), customers, and society. However there are barriers and challenges for OEMs to implement remanufacturing systems. In this sense, Matsumoto [9] identifies the following barriers: an effective collection of used products, development of an efficient remanufacturing process, customer acceptance



**Fig. 1.** Remanufacturing as a technical loop

of remanufactured products, and OEMs do not always have an incentive to remanufacture. In addition, uncertainty is a common condition of remanufacturing systems. The unknown state, quantity, and time to return used products produce a series of process inefficiencies.

The disassembly and assembly processes play an important role in remanufacturing [14]. Disassembling, cleaning, refurbishing, replacing parts (as necessary), reassembling the product, and quality control [13] are common operations to remanufacture a product. Remanufacturing itself is an enormous challenge for any company due to uncertainty in the products' conditions, quantity and the human intensive labor in disassembling [14]. This represents a significant effort of planning and operation by the inherent inefficiencies. Consequently, this challenge has to be faced beyond the traditional manufacturing paradigms to achieve a remanufacturing system design with self-adaptive capacity.

Cellular Manufacturing Systems (CMS) allow to decompose a complex factory into mini-factories or cells, which are manageable units in which groups of product families are manufactured [11, 10]. This paradigm change greatly facilitates the administration and control of the production system, and at the same time, makes it more flexible [7, 12]. Moreover, if we reinforce the system providing features like a reconfigurable manufacturing system, it could manage the demand changes by adding or reducing its capacity [3, 2].

In this sense, the hypothesis defined for this study is: The mix of cellular and Reconfigurable manufacturing architectures in a remanufacturing system could help manage uncertainty in the quantity and product conditions. Hence if the capacity is increased or decreased, the system could keep a constant production rate, avoiding work in process stocks.

That is the core of this study, which describes a hybrid architecture for a cellular reconfigurable manufacturing/remanufacturing system that could adapt itself to different products in variable quantities. This study was synthesized as

a Mixed Integer Non Linear Programming (MINLP) model that integrates cell formation, workload balancing, reconfigurability, and scheduling. A validation process was carried out through a case study modeled in GAMS[1].

The paper is organized as follows: the problem statement is outlined in section 2. In section 3 we introduce a case study. In section 4 the modeling and programming results are analyzed and discussed. Finally, the conclusions of the proposed model and study will be discussed.

## 2 Problem statement

The proposed hybrid architecture mixes cellular and reconfigurable manufacturing features for a remanufacturing system. Cellular manufacturing concepts simplify the system from a plant with complex and aggregated processes to a set of mini plants or cells with a reduced size and complexity. This is possible by defining product families, which share similar processes and product parts, which are assigned to one of the cells in which each product family will be remanufactured completely.

The fluctuations in used products return rates are common in remanufacturing, generating uncertainty. Thereby, it is difficult to forecast a return rate for the used products by the multiple factors involved in the use, status, and final disposal of them. In this sense, this study tries to manage this issue by balancing workloads; modifying cell capacity, adding or removing machines or workplaces to maintain a continuous production rate depending of the processed product. This feature allows the system to adapt to the return rate variations, making it reconfigurable and self-adaptable.

The architecture features were summarized in an optimization model which simultaneously integrates cells and product families formation, workloads balancing, system reconfigurability and production scheduling sequence as is described as follows:

- The strategy carried out for product families and cell definition considers the similarities between products and workplaces were modeled as Hamming distances among them. The minimization of this term allows grouping the workplaces into cells and products into families.
- The system’s reconfigurability is achieved by balancing the workloads by adding or removing workplaces depending on cycle time and product operation times. This allows keeping the production flow constant in each cell.
- Production scheduling is modeled as the lateness, establishing it as the sum of the absolute differences between the product due date and the time to complete.

The model is subject to the following restrictions:

- For the definition of cells and product families, the model must guarantee that each workplace has to be assigned at least to one cell, allowing different cells to have the same workplaces to avoid movements between cells. The

model restricts that each product must belong to a single product family, which at the same time must belong to a single cell.

- Workload balancing needs that the number of workplaces for each product must be greater or equal to ”0” to avoid alternative solutions that exceed the budget for the purchase and installation of workplaces. The model restricts those costs to a maximum budget.
- To achieve feasible solutions in terms of production scheduling and reconfigurability. The solutions must avoid duplication in the production sequences precedence’s, restrict precedence assignments only to products that belong to the same product family.

### **3 Development of the case study**

The process carried out started from the definition of a case study with a unique solution, summarized at table 1. The generation of the ideal case study is based on the following assumptions:

- The remanufacturing system is part of the Original Equipment Manufacturer OEM business strategy.
- The products to be remanufactured have been previously defined and the operations necessary to process them.
- The conditions of the returned products meet the minimum requirements to be remanufactured.
- The remanufacturing system is integrated into a reverse logistics system that allows the return of used products.
- There is a constant demand for the products that define the production sequence.

The analyzed case has 5 types of machines or workstations, 5 products, 5 periods, and 2 cells or product families. This case was generated following the steps described below:

1. We generated an ordered incidence matrix with a diagonal block in which each cell and product family could be identified.
2. We disordered randomly the incidence matrix.
3. The operation times were generated randomly, for each operation defined in incidence matrix.
4. Cycle times were generated, calculating the greatest common divisor from each product’s columns of operation times.
5. The return rate of the used products was generated randomly.
6. We generated the due date following a specific sequence.

The characteristics of the proposed hybrid manufacturing architecture were synthesized in a mathematical model, which was solved for the case study obtaining the schema shown in figure 2. In this schema, the system has two cells that have their own product family. Cell 1 is made up of 6 workplaces type 1,

**Table 1.** Case study

<b>Incidence matrix</b>						<b>Operation times</b>							
		<i>Products</i>							<i>Products</i>				
		1	2	3	4	5			1	2	3	4	5
<b>Workplaces</b>	<b>1</b>	1		1		1	<b>1</b>	450		180		360	
	<b>2</b>		1		1		<b>2</b>		210		340		
	<b>3</b>	1		1		1	<b>3</b>	300		90		60	
	<b>4</b>		1		1		<b>4</b>		140		170		
	<b>5</b>	1		1		1	<b>5</b>	150		270		120	

<b>Return rate</b>						<b>Due date</b>							
		<i>Products</i>							<i>Products</i>				
		1	2	3	4	5			1	2	3	4	5
<b>Periods</b>	<b>1</b>	684	849	197	852	298	<b>1</b>	102600	59430	120330	204270	138210	
	<b>2</b>	197	467	140	757	564	<b>2</b>	167760	236960	180360	365650	214200	
	<b>3</b>	953	141	523	930	737	<b>3</b>	357150	375520	404220	533620	448440	
	<b>4</b>	600	652	577	629	848	<b>4</b>	538440	579260	590370	686190	641250	
	<b>5</b>	110	545	478	708	599	<b>5</b>	657750	724340	700770	844700	736710	

		<i>Products</i>				
		1	2	3	4	5
<b>Cycle time</b>		150	70	90	170	60

2 workplaces type 3, and 3 workplaces type 5; that can be added or removed depending on whether it process product 1,3, or 5, which belong to the family assigned to Cell1. Similarly, cell 2 processes products 2 and 4 and comprises 3 workplaces type 2 and 2 workplaces type 4.

The number of workplaces shown for each cell in figure 2 allows keeping the workloads balanced. It is possible to verify that its value is the result to divide the operation time by the cycle time as is showed in table 2 and figure 3 for product 1. Finally, thanks to workload balancing and system reconfigurability it is possible to maintain a continuous production rate following the production sequence exposed in figure 4.

**Table 2.** Number of workplaces for product 1

<b>Workplace</b>	<b>Operation time</b>	<b>Cycle time</b>	<b>Number of workplaces</b>
<b>1</b>	450	150	3
<b>3</b>	300	150	2
<b>5</b>	150	150	1

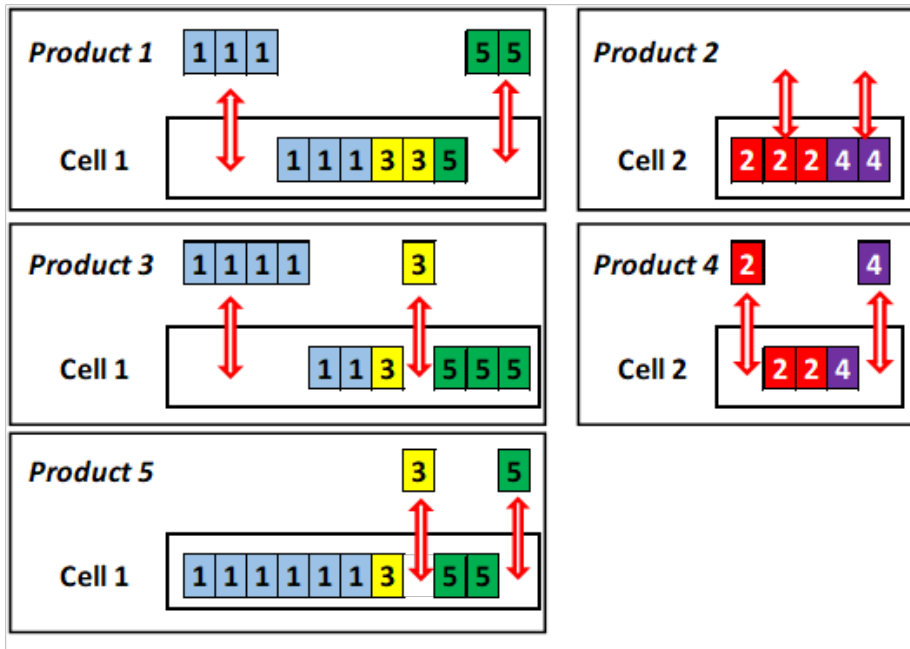


Fig. 2. Schema of Proposed Remanufacturing Architecture for the case study

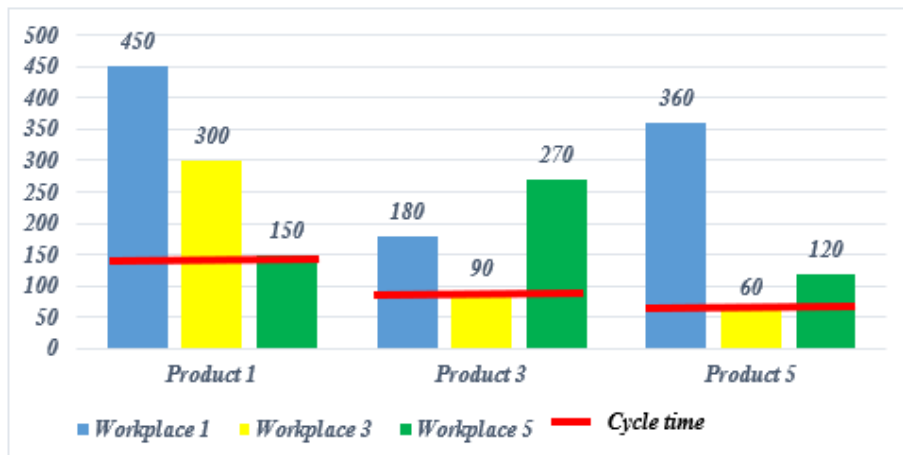


Fig. 3. Operation times for cell 1



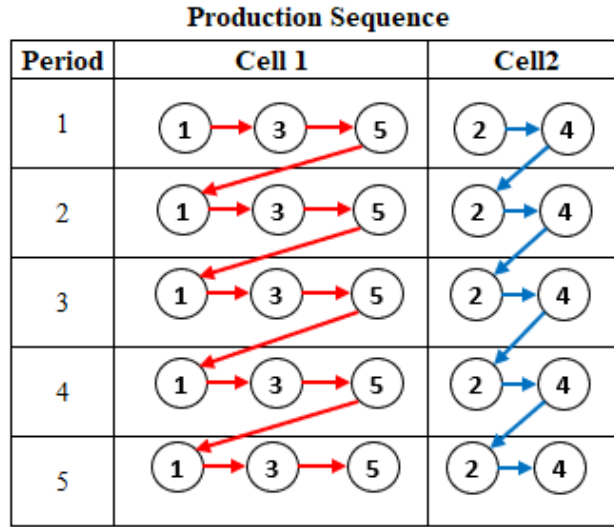


Fig. 4. Production sequence per cell and period for the case study

#### 4 Results analysis and discussion

In this study, hybrid architecture for remanufacturing is discussed, in which the mix of cellular and Reconfigurable manufacturing features are integrated into a remanufacturing system. The generation of manufacturing cells decomposes the system complexity, reducing the variation among the products processed in each cell. This allows each cell to process similar products (product family), sharing workplaces, tools, and equipment. The system reconfigurability is achieved by increasing or decreasing cell capacity depending on the product, which keeps a constant production rate by workload balancing. This feature allows it to manage the uncertainty by adapting the system capacity to the different product conditions and quantities.

The purpose of the hybrid architecture is achieved in its characteristics, supporting the hypothesis of this work as is described in the case study. First, the system's complexity is reduced by generating two cells that fully process the family of products assigned to them (see figure 2). This helps to control the system thanks to the disaggregation of the products return rate in each cell, reducing the impact of variability by quantity or condition of returned products in the throughout manufacturing system, only affecting the cell to which the variable product belong.

The workload balancing allows maintaining a constant flow through each cell, avoiding maintaining work in process; this contributes to the cost reduction derived from inventories, transport and material handling, and even represents benefits for stakeholders by reducing lead times.

Whatever manufacturing system must to be reconfigured when finish a product production and start another. In this architecture system's reconfigurability is a crucial feature which allows to make this task without spend a lot time, thanks to a flexible automated system which make it possible. However, reconfigurability could represent big challenges depending on each workplace's characteristics, by the dimensions, weight, the number of tools or equipment, or even the energy sources, or the management of polluted substances, which need to be analyzed depending on the processes needed, or the complexity of the processed product.

This proposal scope presents limitations by the reduced dimension of the case addressed. Subsequent works require the evaluation of different cases, including industrial data, to verify its applicability or the consideration of a multi-objective focus.

## 5 Conclusions

In this work, a hybrid manufacturing architecture for the design of reconfigurable cellular remanufacturing systems is exposed. This architecture includes the definition of manufacturing cells with their respective product family, thanks to the similarities of the products in the processes required to remanufacture them. The system's reconfigurability is achieved by a automated system which modify the system's capacity, adding or removing workplaces for keeping workload balanced in each cell. In this way, processing times are keeping less than or equal to each product's cycle time. This study is under development, and validation is ongoing with more complex cases and real industrial data.

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