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# Generating Reconfigurable Manufacturing Alternatives from Legacy Factories

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**Abstract:**
Discrete manufacturing companies are challenged to transform their existing manufacturing system to be better prepared for the changes caused by unstable supply chains and new market regulations. Reconfigurable Manufacturing Systems is a manufacturing paradigm conceived to deal with change in a fast and cost-effective way. Most of the design methods for such reconfigurable systems do not take the information of existing manufacturing systems into account. Thus, this paper proposes a method to generate reconfigurable manufacturing alternatives from legacy factories' information. The proposed method uses the bill of materials and the initial production capacity as inputs. The potential use of the proposed method is demonstrated with an illustrative example.



*Keywords:* Design and reconfiguration of manufacturing systems; Decision Support System; Reconfigurable Manufacturing Systems; Brownfield systems; Legacy systems; Bill of Materials; Product family formation; Adaptability.

## 1. INTRODUCTION

Current market and regulation changes, represented by the Green and Digital transitions (Muench et al., 2022), have a great impact on almost all industries, including discrete manufacturing. This triggers companies to adopt more sustainable manufacturing practices (European Comission, 2023), and also to become more resilient in the face of uncertain supply-chain and market conditions (Napoleone et al., 2022). Such a complex scenario pushes manufacturing companies to adapt themselves by performing multiple changes to their manufacturing systems, which can be costly and disruptive to their operations.

Reconfigurable Manufacturing Systems (RMS) is a manufacturing paradigm conceived to allow for rapid and cost-effective change of its physical and logic components (Koren et al., 1999). RMS is considered more flexible than Dedicated Manufacturing Systems (DMS) while still maintaining a high throughput. Such flexibility facilitates the process of introducing new products and even product families, which is deemed crucial for the competitiveness of manufacturing companies (Kashkoush and ElMaraghy, 2016). These characteristics make RMS a promising alternative to DMS and other traditional manufacturing paradigms, especially under uncertain market conditions (Koren et al., 2018). Therefore, it is important to understand how to transform the existing manufacturing systems, which represent an important part of the economy (15% in the EU alone (World Bank Group, 2023)), into more reconfigurable systems.

Different methods have been proposed to design an RMS from scratch (i.e., in greenfield settings), considering multiple configurations of machines in production stages (Koren and Shpitalni, 2010), and taking into account different optimisation objectives and approaches (Yelles-Chaouche et al., 2021). However, few publications address the challenge of transforming existing manufacturing systems into an RMS (i.e., in brownfield settings) (Sorensen et al., 2019; Napoleone et al., 2024). Particularly when considering the problem of changing legacy manufacturing systems, the lack of analytical methods that provide initial RMS layout alternatives represents a significant gap, both in the theory and practice of RMS. Therefore, the main research question to be addressed in this paper is:

*How to develop an analytical method to aid in the initial design of RMS layout alternatives from legacy factories?*

The remainder of this paper is organized as follows. In Section 2 related works are discussed. The proposed method to generate reconfigurable manufacturing alternatives to a legacy manufacturing system is presented in Section 3. An illustrative example is given in Section 4 to demonstrate the potential use of the proposed method. Finally, the conclusions and directions for future research are provided in Section 5.

## 2. RELATED WORKS

The research on RMS design methods can be categorized based on their starting conditions (greenfield vs. brownfield settings), the role of product families, which are crucial for increasing system utilization and productivity (Kashkoush and ElMaraghy, 2014), and the intended users (conceptual methods for experts vs. analytical methods for non-experts). Thus, we analysed part of the RMS


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Table 1. Related works in design methods for RMS.

| Reference | Analytical method | Family formation | Legacy system |
|---|---|---|---|
| Koren and Shpitalni (2010) | ✓ | ∼ | |
| Bryan et al. (2013) | ✓ | ✓ | ∼ |
| Eguia et al. (2017) | ✓ | ∼ | |
| Sorensen et al. (2019) | | ∼ | ✓ |
| Huang and Yan (2020) | ✓ | ✓ | |
| Napoleone et al. (2024) | | ∼ | ✓ |
| This paper | ✓ | ✓ | ✓ |

design literature considering three aspects: the presence of analytical models, the use of product family formation methods, and the use of information from legacy systems, with the findings summarized in Table 1.

The reviewed literature highlights distinct approaches to RMS design methods. Koren and Shpitalni (2010) introduced the first RMS-specific design method, analysing different configurations for multiple machines (e.g., serial lines, cells, crossovers), while Eguia et al. (2017) focused on cell formation with CNC machines and Reconfigurable Machine Tools. Both acknowledged the importance of product family formation, as indicated in Table 1 with a $\sim$, but did not provide explicit methods for it.

In contrast, Bryan et al. (2013) and Huang and Yan (2020) employed methods for defining product and part families, respectively. In Huang and Yan (2020), the authors defined part families based on operational sequence similarities. In Bryan et al. (2013), the authors defined product families based on common base modules and tracked product variation over time. They also affirmed that their method could be adapted to consider prior (legacy) assembly systems as an input.

The methods presented in Sorensen et al. (2019) and Napoleone et al. (2024) were made to consider information (brownfield) legacy systems. Both methods consisted of multiple steps with interviews conducted by RMS experts, being performed in a case study setting, thus being more conceptual and empirical than analytical. The authors in Sorensen et al. (2019) consider the importance of product family information in the development of platforms for changeable manufacturing, but did not provide a method for product family formation. Therefore, to the best of our knowledge, there are no papers presenting RMS design methods that cover all three analysed aspects, with some focused on legacy systems, but not being analytical, and other methods that are analytical but consider the design of an RMS starting from scratch.

## 3. PROPOSED METHOD FOR GENERATING RECONFIGURABLE ALTERNATIVES

In this section, we present an analytical method to generate reconfigurable manufacturing layout alternatives to legacy factories. The proposed method consists of five steps and takes as input commonly available information in a manufacturing context: the bill of materials (BoM) of each product and the current production resources (i.e., the factory's initial capacity). A diagram representing the five steps of the proposed method is shown in Fig. 1. The method transforms the input information in the first step

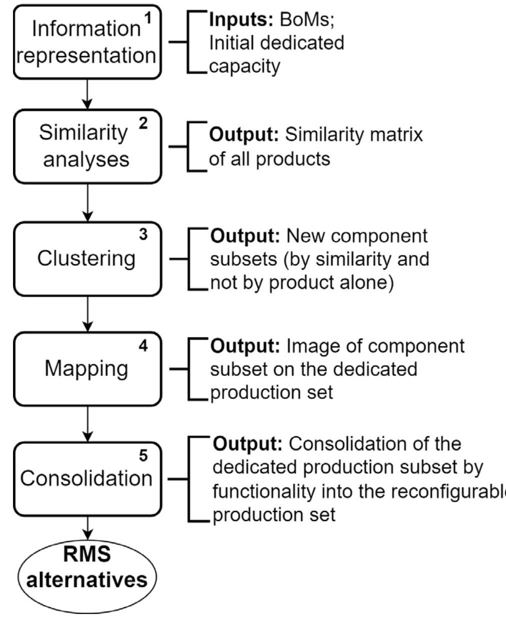



Fig. 1. Diagram of the reconfigurable alternatives layout generation method.

into a common representation to allow for the manipulations in the following steps. The goal is to define product families, following the second and third steps, and then define an alternative reconfigurable layout for each of these product families. In this way, the method is capable of generating RMS layouts from the initial legacy manufacturing system, which we refer to as a reconfigurable alternative.

It is important to highlight the main assumptions taken in the development of this method. Since dedicated production resources have a one-to-one relation with the parts and products they produce, we assume that the current production resources are organized in dedicated lines, or that they could be organized as so (e.g., a fixed group of machines can be identified to be producing a given product at any given time). Thus, if a manufacturing system is composed of highly flexible machines that are constantly making different parts (e.g., a machining shop or 3D printing farm making only one-of-a-kind parts), the proposed method is not suitable since it is not possible to trace a one-to-one relationship with a given product and the machines that made it.

### 3.1 Information representation

The first step in the proposed method is to represent the input information using sets. The BoM of a product is the set of all components and their hierarchical relationships, with the root node being the product itself. Let $P$ be the set of components from some BoMs of interest, with each product representing a subset of components. Consider the case of four products, A to D, as represented in Fig. 2, it is clear that different products share components, as indicated by the intersections between subsets. Some pairs of products do not share any component, like A and D, while others share all their components, like B and C, with B being contained by C ($B \subset C$).

Another set of interest is the initial dedicated capacity $T$, made from different dedicated lines, also shown in

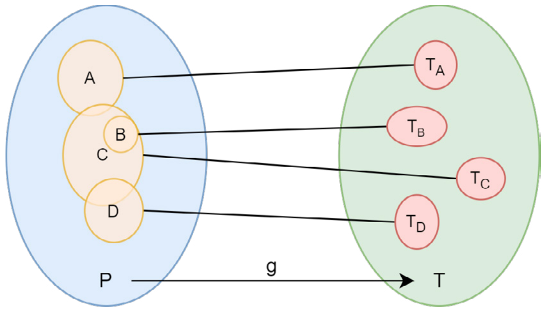



Fig. 2. Product and dedicated resources set representation.

Fig. 2. Each dedicated line, like $T_A$, is formed by various dedicated production resources (or technologies) which can also be present in other dedicated lines but not in the same layout. As the name suggests, the subsets of dedicated lines have a one-to-one relationship with their respective products. Thus, there exists a function $g : X \to Y$ that maps a product to one and only one dedicated resource (i.e., the subsets in $T$ are images of set subsets in $P$ under function $g$). It is important to notice that dedicated line subsets do not overlap by our definition. Even if $T_A$ and $T_B$ could contain similar or equivalent machines, for example, their subsets would remain separate due to the fact they operate independently from each other.

The problem of generating a reconfigurable alternative from a legacy manufacturing system, which is capable of producing the same products as the initial (dedicated) system, can be expressed as finding the set $R$ that is equivalent to the image of the union of all dedicated subsets. Let $f : Y \to Z$ be a function related to the production functionality of a given resource. The image under $f$ of the set $T = \bigcup_i^N T_i$, for $N$ subsets of interest, is the set of all $f[T] = f(t), \forall t \in T$. Thus, we have that $f[T] \equiv R$, which guarantees that $R$ has equivalent production functionalities to $T$. Since the subsets of each dedicated line are the images of their respective products (e.g. $T_A$ is the image of $A$ under function $g$), the new proposed reconfigurable system $R$ should also be the image of a subset of products under a function $h : X \to Z$.

Such formulations provide two ways of defining a reconfigurable alternative, either by looking at the set $X$ of all possible components, using function $h$, or by looking at the dedicated production set $Y$, using function $f$. In Section 3.4 we provide a method to approximate ether these functions by exploring the idea that $f[T] \equiv h[P] \equiv R$, for the set of dedicated lines $T$ and the set of products $P$. Based on this set representation, the remaining steps of the proposed method can be applied.

### *3.2 Similarity analyses*

The second step is to compare all BoMs to check how similar or not all products are. Let $P : p_1, p_2, ..., p_n$ be the set of all products, with $p_i$ a given product and $p_i \subset X$, $p_i \neq \emptyset$, where $X$ is the set of all possible components. Since $P$ is the set of subset of $X$, we can say that $\bigcup_i^N P_i \subset X$. Thus, we can consider the similarity between products in terms of how many elements they share from the set $X$. This can be represented by a similarity function $f : X \times X \to [0, 1]$ defined as

$$f(p_i, p_j) = \frac{|p_i \cap p_j|}{|p_i|} \tag{1}$$

in which the numerator is equal to the number of shared components between the two products, and the denominator is the total number of components of the first product. This implies that $f(p_i, p_j) \neq f(p_j, p_i)$, $\forall i \neq j$ and $p_i \neq p_j$.

Therefore, to perform a complete similarity analysis comparing all products in $P$, we define a matrix $M : N \times N \to M_{i,j} = f(i, j)$. The diagonal elements of this matrix are equal to 1 since a product shares all components with itself, and all other matrix values will be in the interval $[0, 1]$, by the definition of $f$. If a product $p_j$ is a more complex variant of $p_i$ (i.e., $p_j$ have all components of $p_i$ plus some additional ones), than $f(p_i, p_j) = 1$ and $f(p_j, p_i) < 1$.

Other similarity measures could be used, such as the Jaccard index (McAuley, 1972), or even the combination of multiple similarity coefficients, as presented in Kashkoush and ElMaraghy (2014). However, the proposed similarity coefficient, with asymmetry between the values for one product to another, provides important information regarding which product can be seen as a subset of the other, which is useful for the next steps of this method.

### *3.3 Clustering*

Considering the similarity matrix $M$ and a similarity threshold $\delta$, we can define clusters based on the products that are more similar than the threshold, denominated product families. Let $P^C$ be the subset of products that belong to the same cluster, then a particular cluster $k$ can be defined as $P_k^C : \{p_i | M_{i,j} \geq \delta, j \in N\}$ for a set of $N$ products. This definition shows that the procedure to cluster products is straightforward. By looking at the columns of the matrix $M$, we select the rows with similarity values greater or equal to $\delta$ to form a cluster.

Many conditions can be imposed to further alter the initial clusters. For instance, we can introduce a minimum number of products to form a valid cluster or even a maximum number of products if we want to guarantee some degree of separation. It is also possible to merge different clusters using the same approach that created them, by first calculating their similarity and then using another similarity threshold $\delta'$ to determine if they should be merged or not.

The final result of this step is a set of product clusters based on their shared components (i.e., product families). Products that are not in a cluster with other products may not belong to any product family, indicating that they could require a separate production process. Thus, we start by looking for reconfigurable alternatives that satisfy the production needs of the products in large clusters and subsequently try to augment such initial alternatives in order to satisfy the production needs of smaller clusters.

### *3.4 Mapping*

The fourth step consists of defining the functionalities for a reconfigurable alternative, given a set of product clusters. As previously mentioned in Section 3.1, the set of reconfigurable alternatives $R$ is equivalent to the

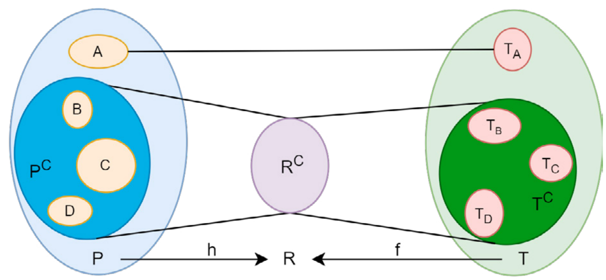



Fig. 3. Mappings from both product subset $P^C$ and dedicated resources subset $T^C$ to the reconfigurable alternative subset $R^C$.

image of the set of products $P$ under a function $h$. For a subset of $P$, namely a product cluster $P^C$, the same mapping $h$ holds, with $h[P^C] = R^C$ where $R^C$ is a reconfigurable production system for $P^C$. Another relation is the one between dedicated production resources and reconfigurable ones, defined by function $f$. Similarly to the case with function $h$, we can write $f[T^C] = R^C$ where $T^C$ is the subset of dedicated lines for the products in $P^C$.

It is evident that, either by defining the function $h$ or $f$, it would be possible to define the subset $R^C$, as indicated in Fig. 3. However, defining such functions for arbitrary sets of products and production resources is very challenging, if not impossible. For instance, we can think about function $h$ as answering the question: What are the reconfigurable resources capable of producing this product? Answering this question directly would require vast expert knowledge on reconfigurable systems for different products, possibly infinity ones.

Similarly, we can think about function $f$ as answering the question: Which reconfigurable resources have equivalent functionalities to this dedicated resource? Again, this would require vast codified knowledge of multiple types of production processes. Thus, it seems unlikely that function $h$ could be explicitly defined, and even if a definition of $f$ could be made, perhaps by a function approximation method (e.g. Multilayer Perceptron and other Neural Network architectures), it would require a vast amount of data.

Nevertheless, we can still determine a reconfigurable alternative $R^C$ without explicitly defining $h$ or $f$, by relying on the unique relationship between the subsets $P^C$ and $T^C$. Since $h[P^C] = R^C$, and $f[T^C] = R^C$, we have that $h[P^C] = f[T^C] = R^C$. Also, given that $g^{-1}[Y]$ is injective (i.e., the preimage of set $Y$ under function $g$ is unique), we have that $g^{-1}[T^C] \equiv P^C$, resulting in the preimage of the dedicated recourse subset. Thus, we can say that the preimage of the reconfigurable alternative subset $R^C$ should contain the same subset $P^C$, that is $h^{-1}[R^C] \supset P^C$, and thus, $h^{-1}[R^C] \supset g^{-1}[T^C]$. This indicates a sufficient condition for the the subset $R^C$, if $R^C \equiv T^C$, than $h^{-1}[T^C] \equiv g^{-1}[T^C] \equiv P^C$, which holds for all $T^C$.

Therefore, as long as $R^C$ has the same production functionalities as in $T^C$, it is guaranteed to be able to produce the subset $P^C$. So, the functionalities in $T^C$ are a sufficient condition for the production of $P^C$. For initial reconfigurable alternatives, there is no need to define a necessary condition (e.g. the minimum set of production functionalities capable of producing $P^C$). Thus we consider the subset $T^C$ as input for the next step to obtain a reconfigurable alternative $R^C$.

### 3.5 Consolidation

The fifth and final step is to consider the different production resources in subset $T^C$ and consolidate them in a reconfigurable structure. This is done by following some of the principles for designing RMS configurations, described in Koren and Shpitalni (2010). Looking again at the representation of $T^C$ in Fig. 3, we can consider that $T_B$, $T_C$, and $T_D$ are composed of multiple machine tools, material handling systems, fixtures, etc. Although we assumed that this subset does not have intersections since they operate independently from each other, we can consolidate resources with equivalent production functionalities.

Thus, by defining a similarity function $h : Y \times Y \to [0, 1]$, analogous to equation (1), we can determine if any two production resources $r_i$ and $r_j$ have similar functionalities or not. The simplest possible function would be a binary discriminator, which would return 1 for resource pair with sufficiently similar functionalities, and zero otherwise. Resources with similar functions are said to belong to the same functionality set.

For simplicity, let us consider only machine tools. Machines that perform similar or equivalent functions (e.g., bending, cutting, drilling) are grouped under the same machine type. These machine type subsets are positioned in the same stages of the reconfigurable systems, as it is arguably impractical to have different types of machines in the same stage (Koren and Shpitalni, 2010). Crossovers and other types of connections are added between different stages to allow for each product's process flow to be as uninterrupted as possible. These two procedures, allocating a given machine type to a stage and connecting all stages, allow us to transform the dedicated configuration into a reconfigurable one since machine types common to different products can be consolidated in the same stage. Therefore, the consolidation process results in a reconfigurable alternative based on (most of) the existing production resources, requiring few additional ones, such as material handling systems for the crossover connections between some stages.

## 4. ILLUSTRATIVE EXAMPLE

In this section, we provide an illustrative example to demonstrate the potential use of the proposed method. Consider a factory producing five products (A to E) made from a total of ten different components (1 to 10). The relation of which components are used in each product is given in Table 2 (i.e., the BoMs). There are seven different machine types (M1 to M7) in this factory, with machines belonging to each type being able to produce at least one of the ten components.

Each product is produced on dedicated lines or cells, which contain all the necessary machines to produce it. A simplified diagram of such a factory is presented in Fig. 4, with five independent lines, one for each product. Notice that each line can be composed of multiple identical parallel lines to arrive at the desired production column of

Table 2. Components in each product (Bill of Materials).

| Product | Component | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| **A** | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| **B** | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| **C** | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 |
| **D** | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 |
| **E** | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 |

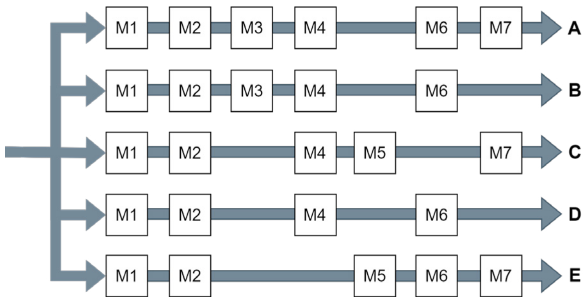



Fig. 4. Dedicated lines producing products A to E.

Table 3. Similarity matrix based on the proportion of components shared between each product.

| Product | A | B | C | D | E |
|---|---|---|---|---|---|
| **A** | 1 | 0.75 | 0.63 | 0.75 | 0.63 |
| **B** | 1 | 1 | 0.50 | 0.83 | 0.50 |
| **C** | 0.71 | 0.43 | 1 | 0.57 | 0.86 |
| **D** | 1 | 0.83 | 0.67 | 1 | 0.67 |
| **E** | 0.71 | 0.43 | 0.86 | 0.57 | 1 |

each product. By applying the proposed method, we can obtain reconfigurable alternatives for the layout of such legacy manufacturing system.

The first step is to gather the necessary information and represent it with sets. Starting with the information from Table 2 and Fig. 4, we define the set of product $P = \{A, B, C, D, E\}$ and the sets of dedicated production resources for each product (e.g., $T_A = \{M1, M2, M3, M4, M6, M7\}$). The set of all dedicated production resources is equivalent to all available machine types $T = \bigcup_{i=1}^{5} T_i \equiv \{M1, M2, M3, M4, M5, M6, M7\}$. The sets $P$ and $T$ contain the necessary information for the next steps.

The second step (similarity analysis) is to calculate the similarity matrix for the products using the similarity function in (1). By applying this function on each product pair in $P$, we obtain the similarity matrix shown in Table 3. It indicates the proportion of components the product shares in each row with the products in each column. For instance, we can see that 100% of the components of product B are shared with product A, with the inverse not being true since only 80% of the components of A are shared with B.

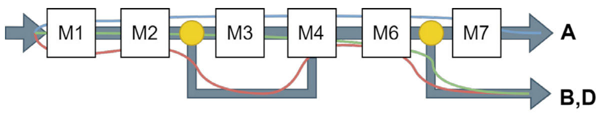
Using the similarity matrix, we can proceed to the third step, defining product families/clusters. Assuming a similarity threshold $\delta > 0.8$, we obtain two clusters, $P_1^C = \{A, B, D\}$ and $P_2^C = \{C, E\}$. The first cluster consists of products A, B and D, with the last two sharing all their components with product A. Thus, we can say that $P_1^C$ represents the set of components in A and two of its subsets. The second cluster does not present the same structure, with products C and E both sharing the same percentage of components ($\approx$ 86%). This indicates that these two products may be variants of a common base product.

The fourth step consists of mapping the clusters from the product set to the production resources set. To do so, we look at the current relation between machines and products, presented in Fig. 4, and define the subset of machines needed to produce each product family. For instance, all machine types but M5 are used to produce the products in $P_1^C$, while all but M3 are needed to produce the products in $P_2^C$, thus, $g[P_1^C] = \{M1, M2, M3, M4, M6, M7\}$ and $g[P_2^C] = \{M1, M2, M4, M5, M6, M7\}$. By looking at the components being produced by each machine, we could determine the set of functionalities which are sufficient to produce each product family. So, if machine M1 is performing face milling operations, while M3 is performing chamfering operations, we can say that a manufacturing system without the chamfering functionality is not capable of producing $P_1^C$, but could be capable of producing product family $P_2^C$, while a system without the face milling functionality is not capable of producing any of the five products.

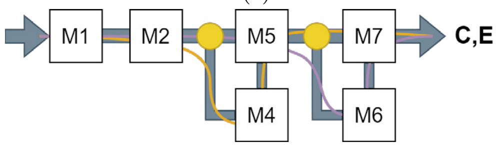
Finally, we apply the fifth step by consolidating the machine cluster into an RMS configuration for each product family. We start by grouping the first common machine types in the same stages for both machine clusters, this corresponds to the machine types M1 and M2. Then, we add other machine types with the necessary connections, making sure that each product's path is respected (i.e., the sequence of machine types that each product must pass through). This can be done by adding crossover connections so that different products can go through different stages and then return to the same common path if needed.

The consolidation of the dedicated lines for product families $P_1^C$ and $P_2^C$ is represented in Figs. 5a and 5b, respectively, with the paths followed by each product being indicated by different colours. Such reconfigurable alternatives are more reliable than the previous dedicated lines since multiple machines of the same type are now used to produce different products, providing redundancy while remaining in use when the system is properly balanced. Also, the reconfigurable alternatives are more convertible, given the ease of changing machines configurations without causing major disruptions to the whole system, and more scalable, with the possibility to add more machines with little effort since they are organised per type in stages, and not per product.

The consolidation process can continue iteratively, using similarities between the newly generated reconfigurable alternatives to merge them into a more streamlined manufacturing system. Since both reconfigurable alternatives presented in Fig. 5 start with the same machine types, namely M1 and M2, we can merge them and form a combined reconfigurable alternative for all the initial dedicated lines. Thus, we can see that the reconfigurable alternative shown in Fig. 6 is capable of producing all five products, with their process paths indicating the same colours as before. The result is a new manufacturing system configu-




(a)




(b)

Fig. 5. Reconfigurable alternatives product families $P_1^C = \{A, B, D\}$, on top, and $P_2^C = \{C, E\}$, on the bottom.

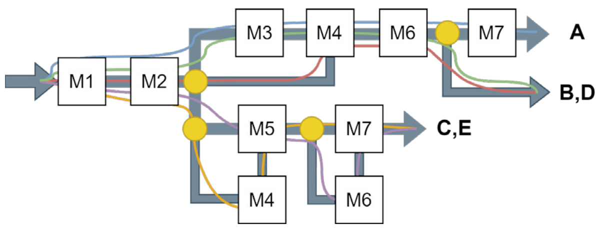



Fig. 6. RMS with coloured lines indicating the path followed by each product.

ration, which uses the same machines as presented in Fig. 4, with some additional buffers and crossover connections. Such alternatives present many advantages, such as an easier and more cost-effective process for introducing new products (especially if they belong to one of the existing product families).

## 5. CONCLUSIONS AND FUTURE RESEARCH

The proposed method addresses the challenge of designing initial RMS layout alternatives for legacy factories. To the best of our knowledge, it is the first method to generate RMS layouts from the information of existing production resources without requiring intensive involvement from RMS experts. The product and production resources set representation ensures the method's generalizability across industries without relying on specific structures or conventions. The dedicated line assumption can be relaxed since it is only instrumental to the set representation and not needed in the physical manufacturing system.

The method provides valuable insights into the transformation process of legacy factories and serves as a foundation for further decision-making and design methods. Future work directions include integrating the method with optimisation techniques, allowing decision-makers to choose the best reconfiguration alternative for a given objective function. Also, simulation methods can be used to evaluate the feasibility of reconfigurable alternatives, supporting capacity planning and factory expansion, and aiding in the introduction of new products or product families. Combining this method with other design tools could enhance product-process co-design and co-development, broadening its potential applications.

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