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Fostering the Reuse of Manufacturing Resources for Resilient and Sustainable Supply Chains

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Abstract: In the current context characterized by turbulent market conditions and the increasing relevance of sustainability requirements, reconfigurable manufacturing systems (RMSs) offer great potentialities for supply chains and networks. While plenty of contributions have addressed RMSs from a technological and system-specific perspective since the mid-1990s, the research interest for the strategic potentialities of RMSs at the supply chain level is recent and mainly related to building supply chains' resilience and sustainability. Despite the interest, methods to support supply chains to strategically exploit RMSs are still missing, while being highly needed. In this paper, a method—consisting of an index to assess machines reusability and a mixed integer programming (MIP) algorithm—is provided to support the identification of reusable and reconfigurable machine candidates at the early stage of the strategic network design. The overall method allows machines to be compared based on their reusability and geographical locations. The application of the method, as well as an example referring to the production of emergency devices during the COVID-19 pandemic are reported. The theoretical and practical implications of the study are also discussed, and, among others, strategic parameters related to machines have been identified and elaborated as enablers of supply chain reconfigurability; the proposed method supports practitioners in improving supply chain resilience and sustainability. The method also encourages practitioners towards the development and adoption of reconfigurable machines. Finally, this study also has social impacts for local communities and stimulates customer-centric collaboration among companies belonging to similar industries and sectors.

Keywords: reconfigurable manufacturing; reuse; resilience; sustainability; supply chain; mixed integer programming

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1. Introduction

Nowadays, specific contextual factors such as the turbulent market conditions and the growing consciousness towards sustainable development are pressuring manufacturers and supply chains. Disruptions arising from many sources including natural disasters, pandemics, exhaustion of resources or geopolitical factors happen rapidly and without warning [1]. Supply chains need resilience, i.e., the adaptive capability to prepare for unexpected events, respond to disruptions and recover from them [1]. For example, during the COVID-19 pandemic, the closing of most of the European borders forced supply chains to reconfigure their networks and manage the emergency by reusing locally available manufacturing resources [2]. Supply chains also aim to enhance network sustainability while ensuring adequate profitability. Historically, encouraged by severe price competition between logistics and transportation companies [3], manufacturers have seized the opportunity to source materials and products internationally in order to reduce their bottom-line cost [4]. Today, supply chains have an increasing interest in reducing their carbon footprint by moving specific manufacturing processes closer to local customers or areas of interest to reduce the environmental impact [5]. This also reduces transportation costs, but may result in prohibitive investment costs.

Reconfigurable manufacturing systems (RMSs), allowing responsive and cost-effective adaptability over time [6,7], offer great potential to enhance supply chains' resilience [8] and environmental sustainability [9,10]. In particular, the modular decomposition of reconfigurable machines makes them adaptable to evolving requirements [10,11] and reusable along the system's life cycle [12]. While research on RMSs at the system/shop floor level is grounded on extensive research since the mid-1990s, the research interest in RMSs as enablers of reconfigurable supply chains appears to be more recent [13–16]. Khan [13] referred to the modularity and scalability of RMSs to assess the impact of these systems on supply chain's delivery performances. Epureanu et al. [14] proposed an algorithm for the interaction between networks for determining the ramp-up time and reconfigurability capacity, thus promoting responsiveness of the RMSs to urgent and unexpected requirements. Belaiche et al. [15] provided an optimization model based on minimum cost and time to create a responsive and effective supply chain process plan in connection with RMSs. Despite the recent interest in showing the benefits of RMSs for supply chains' responsiveness and cost-effectiveness, methods to support supply chains to strategically exploit RMSs are still missing, as also pointed out in existing literature reviews on RMSs [16–19]. Indeed, the strategic parameters related to RMS and manufacturing resources that are relevant to enable network reconfigurability have not been investigated yet, and there is no existing method allowing the comparison of different configuration options based on the reconfigurability and reusability of manufacturing resources. Therefore, this study aims to contribute to filling this gap by addressing the following research question: "How to create a method to assess reusability and reconfigurability of machines, and compare these machines to enable supply chain reconfigurability?".

To this end, this paper is structured as follows. Section 2 investigates the available literature and pinpoints the concepts of reusability, similarity and reconfigurability to ensure responsive and cost-effective network reconfigurations. Section 3 answers the research question by describing the proposed method, consisting of (i) an index to assess the reusability of machines during the strategic network design considering both similarity and reconfigurability; (ii) a mixed integer programming (MIP) algorithm to compare different network configurations based on the reusability and geographical locations of candidate machines to enable responsive and cost-effective supply chain reconfigurations. Section 4 describes the application of the method to improve supply chain resilience and/or sustainability and an illustrative example referring to the production of emergency devices during the COVID-19 pandemic. Section 5 discusses the practical and theoretical implications of the study, and Section 6 concludes and provides directions for future research.

2. Background and Literature Review

Supply chain resilience and sustainability are impacted by the strategic network design phase [20]. Indeed, the configuration or design of the supply chain is a strategic task [21]. Since resilience and sustainability are both extremely relevant to supply chains [20], many studies have addressed the impact of manufacturing resources on these performances; however, these were not in the reconfigurability research domain; in particular, published studies did not investigate the potentialities of reconfigurable resources supporting network reconfigurations. For example, Jabbarzadeh et al. [20] presented a methodology for the design of a sustainable supply network that performs resiliently in the face of random disruptions based on the sustainability performance of the suppliers. Li et al. [22] outlined a mechanism for the impact of manufacturing resources on sustainable development.

In the conducted literature review, two main research domains were investigated through the following search string: "reconfigurable manufacturing" and "supply chain". The search was conducted on Scopus and Web of Science (WoS), as relevant databases to identify scientific contributions. To ensure the identification of the most pertinent articles, papers were filtered by title, abstract and keywords (however, in the search on WoS, this filter was subsequently removed given the restricted publication standards of this specific database). With this procedure, 46 papers were identified (the review is updated to May 2022). The first contributions on the subject date back to 2002. Interestingly, nearly half of the papers (22 out of 46) were written between 2019 and 2022. This further points to the recent interest in exploring the potentialities of reconfigurable manufacturing at the supply chain level, as also stressed in the previous section.

Reconfigurable manufacturing involves the ability to reconfigure at different production levels; these are: (i) the workstation, containing individual operators, machines and/or robots performing a technological operation; (ii) the system, consisting of multiple workstations and material handling systems; (iii) the factory, consisting of production sites; (iv) the supply chain (or network), consisting of multiple sites and transportation systems [23]. As reconfigurability at higher production levels is enabled by reconfigurability at lower production levels [17,24], reconfigurability in network design depends on the reconfigurability at the workstation, system and factory levels.

At each production level, two interrelated domains are: the process and the resource domains. The process domain includes the operations, i.e., the collection of specific tasks. The resource domain includes the technical and human resources that can execute one or more operations [21,25]. Route sheets and operation sheets describe processing sequences for manufactured products (or parts); thus, they describe how the product, whose composing materials are listed in its bill of materials, is transformed and/or assembled through individual operations. Whenever customers demand new or evolved products, manufacturing companies need to assess the ability of the technical and human resources to execute new or changed operations.

In an RMS, part of the technical resources has modular structures (such as reconfigurable machine tools), which makes them adaptable—by adding, removing or replacing modules—to different operations [10]. The key to the profitability of modular resources is the possibility to reuse some of the modules (resource domain), such as standard platforms, along the system's life cycle whenever new requirements in terms of operations (process domain) arise, thus avoiding investments in purpose-built systems [26]. In other words, modular resources are cost-effectively and efficiently adaptable to evolving requirements [8]; thus, they are reusable along their life cycle [9]. In the recent stream of literature on supply chain and reconfigurable manufacturing, Alarcon et al. [11] defined the types of collaborative business models supporting "mobile supply chains", i.e., networks composed of modular and mobile reconfigurable units that can be cost-effectively and responsively moved to different locations, depending on requirements. They also claimed the need for detailed and empirical studies on the subject. Alix et al. [27] also referred to the mobility and modularity of reconfigurable units as a valuable solution to move processes closer to end customers and reduce transportation costs. During the strategic network design, assessing the reusability of candidate resources supports responsive and cost-effective network reconfigurability because the selection of reusable resources would be more convenient than building purpose-built systems [28]. To allow the reusability assessment, resources should be described and coded in a consistent and universal way, following the rules of an established classification, taxonomy, or ontology; an extensive study on the classification and coding of manufacturing systems was conducted by Sorensen et al. [29], who also presented a classification code applicable to different industries and systems intended to facilitate the comparison of resources across factories and support manufacturing reconfigurability. To this regard, visualization and IT systems are also needed to share standard manufacturing information throughout the product life cycle [30,31]. Outside the reconfigurability research domain, specific studies aimed to reveal the impact of information sharing to improve either resilience [32] or sustainability [33].

Both information on the similarity and reconfigurability of resources should be considered and shared to assess their reusability, as these are relevant concepts when responsive and cost-effective network reconfigurations are needed. To the best of the authors' knowledge, in the manufacturing process domain, no existing study has simultaneously considered: resources' reusability (or reuse), similarity and modularity (as key characteristic of reconfigurable resources). In the product domain, which has a higher number of contributions on modularity than the process domain, Galan et al. [34] simultaneously considered these concepts in order to propose a methodology for grouping products into families. In the process domain, researchers have considered either process similarity [35–37] or modularity (an extensive analysis of modularity measures is provided in [38]) in connection to process reusability. Recently, Modrak and Soltysova [38], introduced a relative modularity indicator which, compared to existing modularity indexes, had the advantage of not requiring time-consuming calculation; this was specifically applied to assembly process structures. This concept of relative modularity, based on the foundation that, unlike product modularity, process modularity is not an inherent part of process design but depends on production strategies, has also been considered for the modularity assessment proposed in the next section.

Since a method to strategically assess the reusability and reconfigurability of machines, and compare these machines to enable supply chain reconfigurability has not previously been provided, a new method is proposed below to fill the identified gap.

3. Method Proposal

According to the aim of this study and based on the literature review, supply chain resilience and sustainability are desired performances enabled by network reconfigurability. As shown in Figure 1, supply chain reconfigurability is in turn affected by technical resources, as these encapsulate high investment costs compared to human resources. Thus, during the strategic network design, it is relevant to assess the reusability of technical resources, based on both the concepts of similarity and reconfigurability.

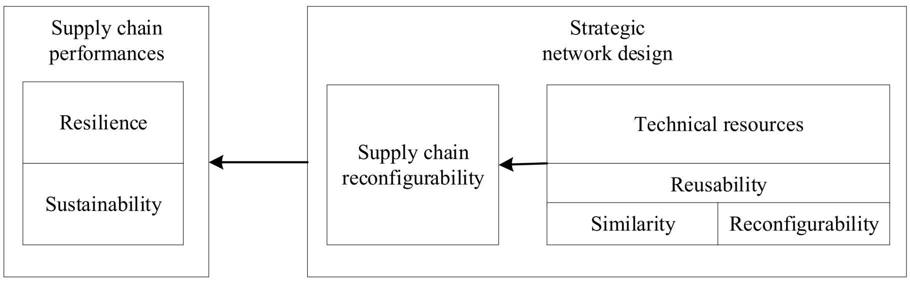

Figure 1. Framework of concepts used to develop the proposed method.

The proposed method consists of a new index to assess the reusability of technical resources, which is used in a mixed integer programming (MIP) algorithm to compare different network configurations and support the identification of reusable and reconfigurable resource candidates at the early stage of the strategic network design. The application of the overall method to improve supply chain resilience or sustainability is discussed in Section 4. As illustrated in Section 3.1, for a needed operation type, the reusability index of a candidate resource is a number within the interval [0, 1]; its quantification is based on the assessment of both: (i) the similarity of the candidate with a selected benchmark resource and (ii) the reconfigurability of the candidate. As illustrated in Section 3.2, for each of the needed operation types, the reusability index is one of the inputs of the MIP algorithm; the algorithm also considers the geographical locations of candidate resources and their distances from areas of interest in order to identify and select, for each needed operation type, those candidates having the highest reusability index within the areas of interest.

3.1. Reusability Index

To support the strategic network design phase, the reusability assessment should be based on a few essential parameters describing the technical resources, i.e., the machines at the workstation level. For the remainder of this paper, “machine” is generically used to refer to either a machine or a robot changing (including joining and mechanical fastening) one or more physical and/or chemical characteristics of the input product or part according to the operation sheets. Machines usually entail high investment costs and greatly affect the reconfigurability potentialities at network level.

Based on the classification code proposed by Sorensen et al. [29], four features, describing a machine at workstation level, its relationship with the operations (process domain), and with a few selected properties of the output, are chosen in this study:

- the general description of the machine functionality (GMF), i.e., the operations that can be executed by the machine. Depending on the specific machine, GMF can either be: (i) transformations which modify the geometry, mechanical and/or physical properties of products or parts; (ii) assembly operations, in which two or more separate parts are joined to form subassemblies or products [39];
- the interval representing the range of sizes of the output products or parts (RS);
- the list of different materials of the output products or parts (RM);
- the production capacity of the machine (PC), representing the relationship between the machine functionality and the overall output volumes.

GMF could be described through the classification code related to workstations, and specifically machines, provided by Sorensen et al.; regardless, the way GMF, RS, RM and PC should be coded in a consistent and universal way is considered outside the scope of the present study, while the reason for their inclusion in the essential parameters supporting the early stage of the strategic network design phase is hereafter justified, specifically: GMF allows the comparison between machines (in the resource domain) based on the needed operations (thus the process domain); RS and PC are also included because product or part size and production volumes are the main drivers for the design of manufacturing systems and greatly impact the physical characteristics of technical resources [6,29]. The features RS and PC also permit implicit consideration of other technical resources such as material handling system (e.g., the RS property drives size and type of handling systems). Finally, the RM feature is included due to the increasing relevance of sustainability requirements, which are leading companies, for example, to replace pollutive materials with sustainable or recycled ones.

Considering the operation i, implemented by the machine X_i, the assessment of the reusability of another machine Z_i requires the evaluation of the similarity between its functionality and the functionality provided by X_i. X_i could also be a selected benchmark machine for executing the operation i. The reusability of Z_i also depends on its reconfigurability, thus on its modularity [12,16].

In this study, the reusability index γ_i (X_i, Z_i) of a candidate machine Z_i is calculated through the similarity $S_i(X_i, Z_i)$ and reconfigurability $R_i(Z_i)$ vectors, where:

- $S_i(X_i,Z_i) = [s_{i1}; s_{i2}; s_{i3}; s_{i4}]$;
- $R_i(Z_i) = [r_{i1}; r_{i2}; r_{i3}; r_{i4}]$.

The four components s_{ij} and r_{ij} of the two vectors can assume binary values that are set considering, respectively, GMF, RS, RM and PC. Specifically, the components of $S_i(X_i, Z_i)$ are defined by comparing the machine X_i with the candidate Z_i:

- $s_{i1} = 1$ if GMF of Z_i equals the GMF of X_i, otherwise, $s_{i1} = 0$;
- $s_{i2} = 1$ if RS of Z_i contains the RS of X_i, otherwise, $s_{i2} = 0$;
- $s_{i3} = 1$ if RM of Z_i contains the RM of X_i, otherwise, $s_{i3} = 0$;
- $s_{i4} = 1$ if PC of $Z_i \geq$ PC of X_i; otherwise, $s_{i4} = 0$.

Moreover, $\sigma_i(X_i, Z_i) \in [0, 1]$, the similarity index of Z_i with X_i in the current configuration, is introduced and calculated as follows:

- $\sigma_i(X_i,Z_i) = \sum_{j=1,\ldots 4}(\omega_j s_{ij})$ where
- $[\omega_1; \ldots ;\omega_4]$: $\sum_{j=1,\ldots 4}(\omega_j) = 1$ are context-specific weights given to GMF, RS, RM and PC.

To assess machine reusability considering jointly similarity and modularity, in this study, machine reconfigurability is evaluated according to the possibility to add, remove or replace modules in order to implement the required operation.

The components of $R_i(Z_i)$ do not require a comparison between X_i and Z_i, but their definition depends on the operation i and on the modularity of Z_i, specifically:

- $r_{i1} = 1$ if GMF of Z_i can be changed by replacing one or more modules of Z_i, otherwise, $r_{i1} = 0$;
- $r_{i2} = 1$ if RS of Z_i can be changed by replacing one or more modules of Z_i, otherwise, $r_{i2} = 0$;
- $r_{i3} = 1$ if RM of Z_i can be changed by replacing one or more modules of Z_i, otherwise, $r_{i3} = 0$;
- $r_{i4} = 1$ if PC of Z_i can be changed by adding/removing one or more modules of Z_i, otherwise, $r_{i4} = 0$.

In the mathematical formulation, the reusability index is a function of the machine similarity and reconfigurability $\Upsilon: SxR \rightarrow [0, 1]$; $\Upsilon_{i,k(i)}$ (X_i, Z_i) is calculated as follows:

- $\Upsilon_i(X_i, Z_i) = \sigma_i$ if $\sigma_i = 1$;
- $\Upsilon_i(X_i, Z_i) = \sigma_i + [(\neg S_i) \cdot R_i]/4$ if $\sigma_i < 1$

where $(\neg S_i)$ is a four-component vector, representing the Boolean negation of the similarity vector $S_i(X_i, Z_i)$; thus, in the formula, the term $[(\neg S_i) \cdot R_i]/4$ is the scalar product of two vectors, divided by 4 which is the cardinality of the vectors.

Concluding, the four essential features (GMF, RS, RM and PC) have been specifically selected since the proposed reusability index is intended for strategic use by networks of companies. Moreover, the attribution of binary values to the components of the similarity $S_i(X_i, Z_i)$ and reusability $R_i(Z_i)$ vectors is aligned with the aim to provide an assessment tool in the indispensable early stage of network configuration: the identification of suitable (reusable, thus profitable) candidate machines. The use of binary values not only makes the use of the tool easier, but it also supports fast identification of the most promising reusable machines. A subsequent phase of analysis of the candidates may be required, where additional detailing information could be added (see for example [29,40]). The presented assessment can be easily adjusted to address other manufacturing resources and/or include different features in order to support detailed and operational decisions (rather than comprehensive and strategic ones as aimed in this study).

3.2. Mixed Integer Programming (MIP) Algorithm

The proposed MIP algorithm (Algorithm 1) allows the comparison of different network configurations. The problem's data, parameters, decision variables and MIP formulation are defined below.

Algorithm 1. The Proposed Algorithm

Data

- $O = (o_1, \ldots, o_n)$, set of the n needed operation types given by the route and operation sheets
- M, set of machines
- $X_i \in M$, $i = o_i \in O$, benchmark machine or machine currently implementing o_i
- $Z_{i,k(i)} \in M$, $k(i) = (1, \ldots, m_i)$, set of the m_i candidates that could execute o_i
- C, centroid representing an area of interest (e.g., location of the customer)
- LM, set of locations of machines M including C

- $D(a, b)$ = distance between a and b, $a, b \in LM$
- $D(C, Z_{i,k(i)})$, $\forall\ i \in O$, distance between candidates and C
- $D(Z_{i,k(i)}, Z_{l,k(l)})$, $i \neq l \in O$, distance within candidates pertaining to different operation types
- $0 \leq Y_{i,k(i)} \leq 1$ reusability index of $Z_{i,k(i)}$ (calculated based on X_i and $Z_{i,k(i)}$ as illustrated in Section 3.1)

Parameters

- v, maximum admissible distance between a candidate and C
- w, maximum admissible distance within candidates (optional).

Decision variables

- $z_{ik(i)} = 0/1$ $k(i) = (1, \ldots, m_i)$, binary variable corresponding to a candidate $Z_{ik(i)}$ $\forall\ i \in O$

MIP formulation

$Min\ D(C, Z_{ik(i)})\ k_i = (1, \ldots, m_i)$	Algorithm Phase 1	(1)
$Max\ (Y_{ik(i)}\ z_{ik(i)})\ k_i = (1, \ldots, m_i)$	Algorithm Phase 1	(2)
$D(C, Z_{i,k(i)}) \leq v$	Algorithm Phase 1	(3)
$z_{1k(1)} + \ldots + z_{nk(n)} = n$	Algorithm Phase 1	(4)
$D(Z_{i,k(i)}, Z_{lk(l)}) \leq w\ i \neq l \in O$	Algorithm Phase 2 (optional)	(5)

Figure 2 represents the relationship between O, set of the n needed operation types and M, set of machines, including current machine X_i and the set of the replacing candidates $Z_{i,k(i)}$.

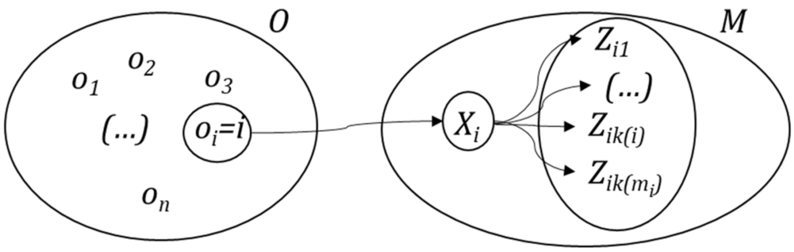

Figure 2. Representation of the sets O, needed operation types, and M, machines.

In the first phase of the algorithm, for the first operation $i \in O$, the objective (1) is to identify the candidate $Z_{i,k(i)}$ having minimum distance from the centroid C representing the area of interest. The objective (2) aims to identify the candidate $Z_{i,k(i)}$ with maximum reusability, considering similarity and reconfigurability to replace machine X_i. Since the two objectives might be conflicting, the objective (1) can be replaced with the constraint (3), which, depending on the parameter v, defines the maximum admissible distance between the candidate $Z_{i,k(i)}$ and the centroid C. Indeed, when distance $D(C, Z_{i,k(i)}) > v$, then $z_{i,k(i)} = 0$, while when distance $D(C, Z_{i,k(i)}) \leq v$, then $z_{i,k(i)} = 1$; thus it represents an admissible solution.

When the identification of the $z_{i,k(i)}$, which maximizes the objective (2), is completed for the first operation i, a subsequent operation $i + 1$ is considered, and this is reiterated until candidate machines are investigated for all n required operations $i \in O$. The constraint (4) verifies that a candidate machine is selected for all n operations. If the constraint (4) is not satisfied, it has not been possible to identify reusable candidates for one or more operations. In that case, the decision maker should modify the parameter v, thus enlarging the space of admissible solutions.

Phase 2 of the algorithm can be optionally implemented; by introducing the constraint (5), the set of admissible solutions is potentially reduced and a new optimal solution might be identified. Indeed, (5) ensures that the internal distance between candidate machines pertaining to the required operation types is lower than the parameter w.

3.3. Decision Logic of the Method

The decision logic of the overall method, including reusability assessment and MIP algorithm (only phase 1 is represented), is reported in Figure 3.

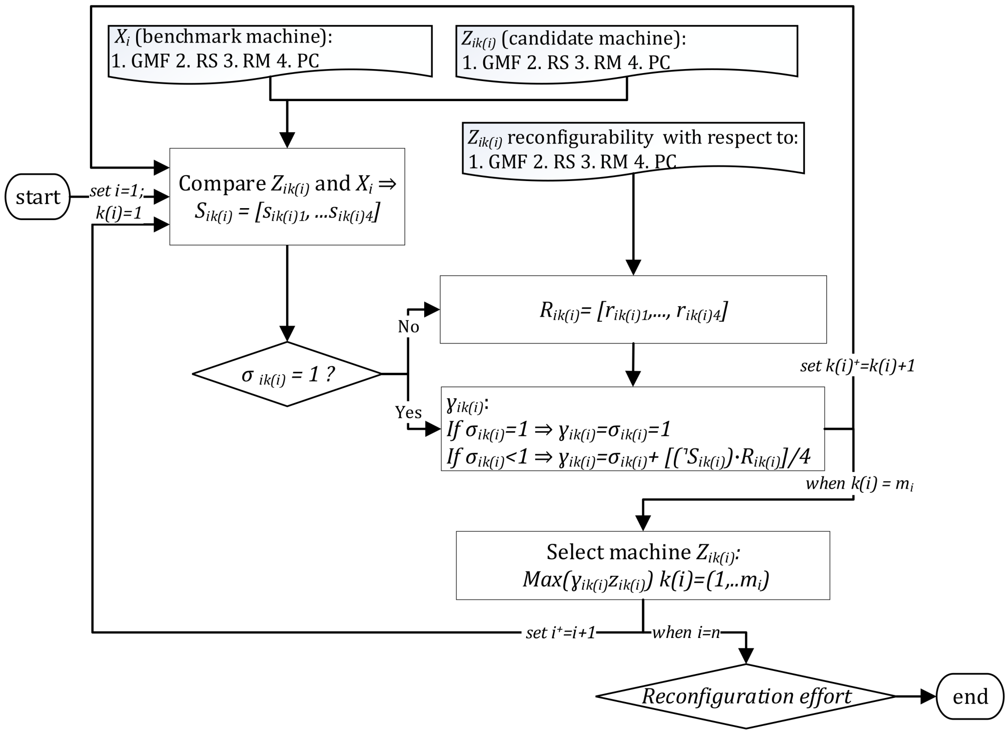

Figure 3. Decision logic of the proposed method.

Figure 3 shows that, for an individual operation $i \in O$, information about the GMF, RS, RM and PC, in the form of coded items, are used to compare each candidate machine $Z_{ik(i)}$, $k(i) = (1, \ldots, m_i)$ and X_i and calculate $S_{ik(i)}$; the reconfigurability of $Z_{ik(i)}$ is calculated whenever $\sigma_{ik(i)} \neq 1$, based on the coded information about the reconfigurability of $Z_{ik(i)}$. The candidate $Z_{ik(i)}$ with maximum reusability $\Upsilon_{i,k(i)}$ is selected, and the same procedure is reiterated for each operation $i \in O$. The procedure is initialized with the first needed operation $i = 1$ and related candidate machines and ends with the last needed operation $i = n$ and related candidate machines.

4. Application of the Method

The application of the method, including the interpretation of the parameters, as well as the illustrative example, are described in this section. The method allows machines to be compared based on their reusability and geographical locations and can therefore be used to improve supply chain resilience and sustainability. Indeed, the preliminary identification of the areas of interest might depend on the supply chain's need to: (i) resiliently reconfigure a network after a major disruption or (ii) move manufacturing processes within areas of interest (e.g., closer to local customers) to reduce the network carbon footprint.

4.1. Interpretation of the Parameters of the Method

In the proposed method, parameters $\Upsilon_{i,k(i)}$, v and w have the following interpretation. Considering the economic interpretation of $\Upsilon_{i,k(i)}$:

- when the reusability index $\Upsilon_{i,k(i)}$ tends towards 1, the cost of replacing the X_i with $Z_{i,k(i)}$ decreases due to the possibility to reuse existing modules;

- if $\sigma_{i,k(i)} = 1$, there is no reconfiguration cost;
- if $\sigma_{i,k(i)} < 1$, a reconfiguration cost is added; it depends on $(\check{S}_i)$, but it is usually lower than investing in a purpose-built system.

The parameter v, the maximum admissible distance between a candidate and C, can be a pure or weighted geographical distance, estimating the maximum admissible cost associated with the transportation. More importantly, the definition of v might be driven by the supply chain's requirements in terms of resilience or sustainability.

The economic interpretation of the parameter w, the maximum admissible distance within candidates, is coherent with the impact of v.

The decision maker can repeat several times the MIP algorithm by progressively reducing the parameter v from a starting value to a minimum value. The starting value v may be the distance between the machines currently implementing the needed operations and the area of interest. The minimum value of v is constrained by the identification of admissible solutions. By setting an adequately low value of v, the identified machines determine a reduced transportation cost due to the lower distance from areas of interest.

Furthermore, defining the space of admissible solutions, the parameter v indirectly impacts on the reconfiguration costs, which are captured by the reusability index $\gamma_{i,k(i)}$. This index, together with the parameter v, allows an economic comparison of the admissible solutions.

When the second phase of the algorithm is implemented, the decision maker can repeat the algorithm by progressively reducing the parameter w. The parameter w impacts on the transportation cost by considering the distance within the machines of the identified solution. Therefore, w ensures the identification of an adequately low number of companies providing the required machines. Additionally, the parameter w, together with the reusability index $\gamma_{i,k(i)}$, supports an economic comparison of the admissible solutions.

4.2. Illustrative Example

The illustrative example is contextualized in the COVID-19 pandemic that forced communities to identify local resources to face the emergency. The exhaustion of relevant resources that drives the green transition determines a situation analogous to the COVID-19 and other health emergencies, as these situations revolve around the need to rapidly identify and exploit replacement resources. Similarly, geopolitical turbulences, such as wars and embargos, require the identification of alternative network configurations.

Due to the closing of borders, local companies need to cluster into a local supply chain in a country F to produce mechanical ventilators, which are highly needed in the great majority of national hospitals [10]. National hospitals have centroid C. Specifically, bi-level positive airway pressure masks are needed; in this scenario, a global company *GC* provides the masks' moulding process, i.e., machine X, at manufacturing sites located outside country F, while all other machines are already provided by local companies. In the MIP formulation, the objective (1) is replaced with the constraint (3) and the parameter v is introduced in order to ensure that the replacement machines will be located in the country F. Thus, the functionality of X, provided by *GC*, is described in Table 1, reporting the general machine functionality (GMF), the range of sizes and shapes of the output parts (RS), the range of materials of the output parts (RM) and the relationship between the machine functionality and the overall output volumes (PC). Table 1 also shows the distance between the machine provider and the centroid C as a function of the parameter v = 300 km. The local companies *Alpha*, *Beta* and *Gamma*, provide the same information for their candidate moulding processes, respectively, Z_{alpha}, Z_{beta} and Z_{gamma}, as reported in Table 1. Table 1 also shows the admissibility of the binary variables z_{alpha}, z_{beta} and z_{gamma}, as they satisfy the constraint (3). The three companies also provide information about machine reconfigurability with reference to machine functionality GMF, RS, RM and PC, as summarised in Table 2. The data in Tables 1 and 2 are used to calculate the reusability indexes γ_{alpha}, γ_{beta} and γ_{gamma} shown in Table 3. In this example, the context-specific weights are assumed equal ($\omega_j = 0.25$). The MIP algorithm selects the *company Gamma*, as it maximizes the objective (2), and minimizes the reconfiguration cost.

Table 1. Machines' functionalities and distances.

	GMF	RS	RM	PC	Distances
X	Processing—shaping—solidification—moulding	Height: 80–115 mm Width: 56–66 mm	Plastics	~300 per month	$D(C, X) = 1200$ km $> v$
Z_{alpha}	Processing—shaping—solidification—casting	Height: 30–800 mm Width: 10–300 mm	Metal	~1000 per month	$D(C, Z_{alpha}) = 250$ km $\leq v$ $D(LN, Z_{alpha}) = 50$ km
Z_{beta}	Processing—shaping—solidification—moulding	Height: 200–1000 mm Width: 100–600 mm	Plastics	~400 per month	$D(C, Z_{beta}) = 110$ km $\leq v$ $D(LN, Z_{beta}) = 100$ km
Z_{gamma}	Processing—shaping—solidification—moulding	Height: 500–1000 mm Width: 100–300 mm	Plastics	~500 per month	$D(C, Z_{gamma}) = 160$ km $\leq v$ $DN(LN, Z_{gamma}) = 73$ km

Table 2. Candidate machines' reconfigurability.

	GMF	RS	RM	PC
Z_{alpha}	No; to change it, the whole machine should be replaced	Not outside the range specified in Table 1	Not outside the range specified in Table 1	No; to change it, the whole machine should be replicated/removed
Z_{beta}	No; to change it, the whole machine should be replaced	Not outside the range specified in Table 1	Not outside the range specified in Table 1	No; to change it, the whole machine should be replicated/removed
Z_{gamma}	No; to change it, the whole machine should be replaced	Yes; a 3D printer is used to construct new moulds, extending the range of sizes of parts	Not outside the range specified in Table 1	No; to change it, the whole machine should be replicated/removed

Table 3. Calculation of Y_{alpha}, Y_{beta} and Y_{gamma}.

	Z_{alpha}	Z_{beta}	Z_{gamma}
S_i	$(s_1 = 0, s_2 = 1, s_3 = 0, s_4 = 1)$	$(s_1 = 1, s_2 = 0, s_3 = 1, s_4 = 1)$	$(s_1 = 1, s_2 = 0, s_3 = 1, s_4 = 1)$
σ_i	0.5	0.75	0.75
$\bar{S}_i$	(1, 0, 1, 0)	(0, 1, 0, 0)	(0, 1, 0, 0)
R_i	$(r_1 = 0, r_2 = 0, r_3 = 0, r_4 = 0)$	$(r_1 = 0, r_2 = 0, r_3 = 0, r_4 = 0)$	$(r_1 = 0, r_2 = 1, r_3 = 0, r_4 = 0)$
Y_i	0.5 + 0 = 0.5	0.75 + 0 = 0.75	0.75 + 0.25 = 1

In the second phase of the algorithm, the constraint (5) is added; since all other companies involved in manufacturing the masks are already located in *country F*, the centroid *LN* representing the location of the local network is introduced. Constraint (5) is set as $D(LN, Z_k) \leq 75$ km. Table 1 reports these distances. The algorithm excludes *company Beta*. Figure 4 represents the solution in the Euclidean space considering the constraint (5), with respect to the distance $D(LN, Z_k)$, and the complement to 1 of the reusability index Y. It shows that *company Alpha* has the lowest distance from *LN*; it also shows that *company Gamma* has the highest reusability index. After the addition of (5), *company Gamma* is still in the admissible domain, and it is selected by the algorithm as it maximizes (2). Then, a more detailed analysis of the needed reconfiguration effort should follow; this might eventually lead to the modification of the parameters of the algorithm and/or the removal of specific candidates in order to re-run the algorithm so as to explore new solutions.

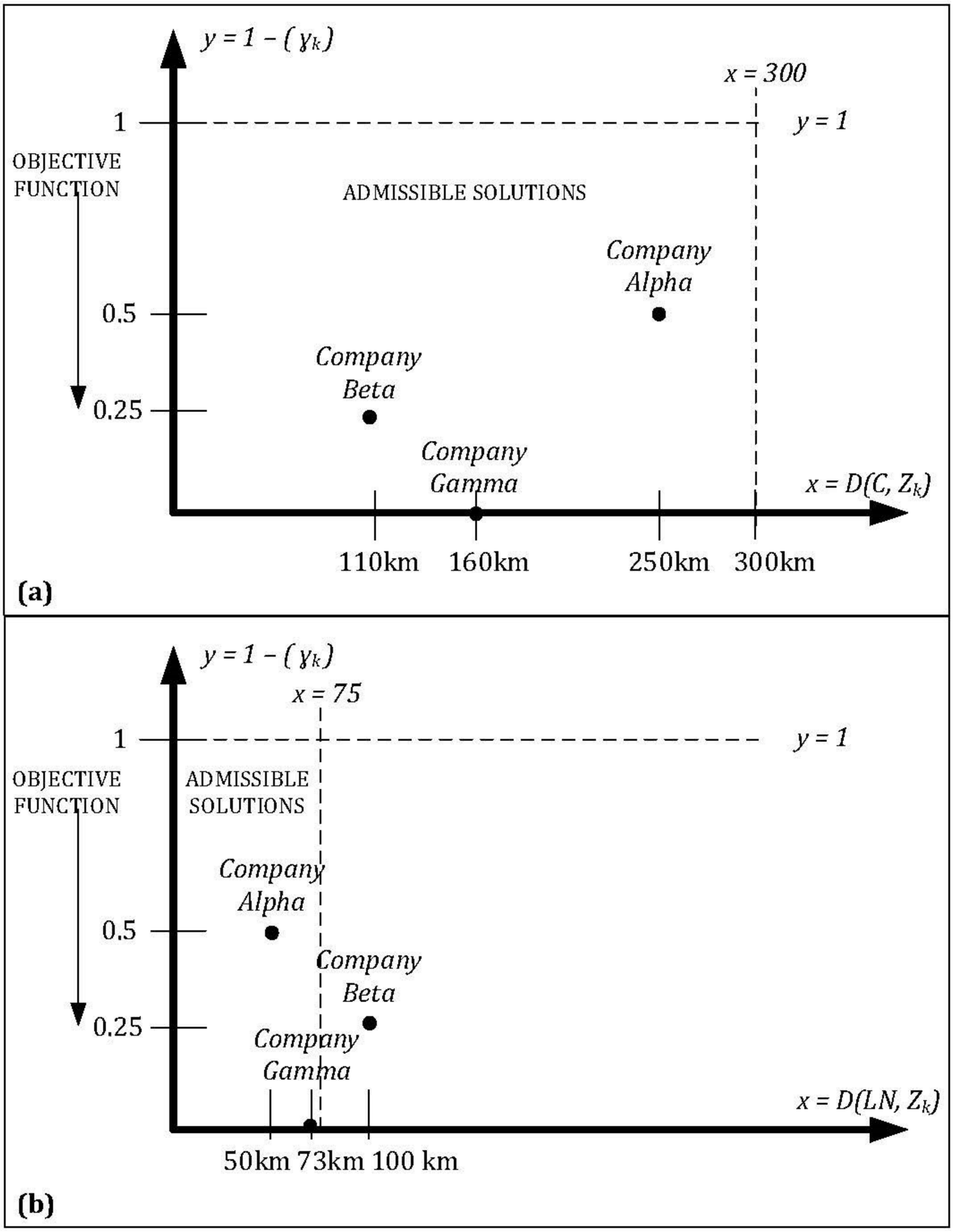

Figure 4. Representation of the solution in the Euclidean space. (**a**) shows the distance from the centroid *C* and (**b**) shows the distance from the centroid *LN* representing the location of the local network.

5. Discussion

From a theoretical perspective, this study contributes to the recent stream of research addressing the benefits of RMSs for supply chains' responsiveness and sustainability. This study also contributes by showing how RMSs enable strategic supply chain reconfigurability based on their reusability. Indeed, relevant parameters related to machines, i.e., the general functionality, the range of sizes and materials and the production capacity have been used to assess machines' reusability based on similarity and reconfigurability.

Moreover, the mixed integer programming (MIP) algorithm supports the identification of reusable and reconfigurable candidates at the early stage of the strategic network design. Thus, it contributes to filling the existing research gap identified in Section 1. Finally, this study implicitly remarks on the relevance of IT systems and information sharing in the Industry 4.0 era, and encourages the development of ontologies and standard classifications aimed at supporting companies with resilient and sustainable collaboration.

From a practical perspective, the proposed method supports practitioners in identifying reusable and reconfigurable machines when aiming to improve supply chain resilience and sustainability. Indeed, due to either an unexpected disruption or aiming to reduce the carbon footprint of a supply chain, companies might need to move a number of manufacturing processes in specific areas of interest, and they would be interested in identifying reusable machines to ensure responsive and cost-effective network reconfigurations. The method can be used in a versatile way by:

- an individual company that aims to modify the configuration of its production sites, in order to compare machines when establishing new sites or designing a new network of sites. It permits candidate solutions to be compared with respect to the associated reconfiguration and transportation costs;
- a network of companies.

Therefore, the method supports the dynamic clustering of manufacturing sites or companies into industrial networks, thus ensuring higher resilience towards sudden changes.

The method also supports supply chains and networks to adopt more environmentally sustainable configurations because it provides a procedure to move manufacturing processes in specific areas of interest (e.g., closer to local customers), consequently reducing the carbon footprint of the supply chain due to the transportation of products or parts. Moreover, as supply chains aim to enhance network sustainability while also ensuring adequate profitability, the fact that the algorithm aims at identifying the candidates with maximum reusability supports the identification of cost-effective network configuration options.

Finally, the method aims to encourage practitioners towards the development and adoption of modular and reconfigurable machines, as these can be reused along the system's life cycle, opening them up to new business opportunities.

6. Conclusions and Outlook

The turbulent and unpredictable geopolitical context has recently had a relevant impact on the manufacturing industry and demands for resilient and sustainable supply chains. This study provides a method for manufacturing companies to assess machine reusability and an MIP algorithm supporting the identification of reusable and reconfigurable machine candidates at the early stage of the strategic network design. The overall method allows machines to be compared based on their reusability and geographical locations and can therefore be used to improve supply chain resilience and/or sustainability.

Collaboration among different manufacturers is a key aspect in the proposed method. To this regard, manufacturers' profitability lies in both the reuse of local machines rather than investing in local systems purpose-built, and the reduction in logistics and transportation costs. The reliance on the availability and sharing of structured information is another critical aspect of this study. In the Industry 4.0 era, companies should be able to share standard information about manufacturing resources; however, the digitalization level of many manufacturing companies is still under development. To this end, governments and organizations should encourage the diffusion of databases, where each company could share standardized information to collaborate resiliently and sustainably. This would also require new managerial approaches. Moreover, governments and organizations should foster the diffusion of methods to assess the appropriateness of currently adopted IT systems, as well as the availability/establishment of the data to allow resilient and sustainable collaborations.

Concerning the impact of this study, the proposed method leads to the following consequences:

- the promotion of social sustainability thanks to the creation of value for local communities, also ensured by the collaboration with local companies, which have more insights on local customers and local economies.
- the fostering of new business models where capacity sharing permits not only a reduction in the total capital assets of the involved companies, but also network resilience and sustainability to be enhanced.

Regarding the limitations of the study, the proposed reusability assessment relies on a limited number of essential parameters referred to the machines and on the attribution of binary values, which implies fast exclusion of several candidates. However, the selected choices and simplified assumptions were carefully made given the aim to support strategic network reconfigurability. Moreover, as discussed in Section 3, the proposed method can be easily adjusted to include different features and specific analyses. A limitation of the overall method is the specific focus on machines as the main source of investment costs during the strategic network design; other sources of investments might need consideration, also depending on sectors and industries, and this is certainly an aspect that could be investigated in future research.

Other directions for future research are: to apply the proposed method in industrial contexts; mature the reusability index to enable accurate evaluations of reconfiguration costs and efforts; directly connect the method to the quantification of the impact of supply chain resilience and sustainability.

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