# Modeling reconfiguration costs and duration in manufacturing plants for resilience enhancement

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**Abstract**: The uncertainty of current competitive environment asks for the capability of manufacturing systems to adapt to changing market conditions. Moreover, the current interest of scholars towards the concept of plant resilience testifies the relevance given to the analysis and quantification of adaptive and restorative capabilities of production systems. While resilience research at first focused on disruptions causing physical damage to production plants, i.e. as caused by natural hazards like earthquakes, recently, disruptions in suppliers side or market demand have been incorporated in resilience modeling. To adapt in case of suppliers interruption or marked changes in customers demand asks for a reconfiguration of the production system in order to modify the manufacturing cycle to accommodate different input materials or the inclusion of new products in the production mix. Drastic change of the manufacturing system in turn determines additional expenditures as well as production interruption. To allow economic evaluation of reconfiguration efforts as well as the impact of production interruption on plant resilience, a model has been developed to estimate capital and operating expenses of reconfiguration processes as well as the time trend of capacity reconfiguration based on the actual process structure and the schedule of reconfiguration tasks as dictated by logic constraints in their implementation sequence. This allows to quantify lost production cost, and reconfiguration duration in order to assess resilience to market changes or suppliers disruption. The model identifies resources to be reconfigured on the basis of a comparison of current and future process plan, and correspondingly computes labor costs, lost capacity costs, and investment/salvage costs due to system reconfiguration and ramp-up and time-based capacity curve during the reconfiguration activities. In the paper following the description of the mathematical model, a numerical application example is included to exemplify the computational procedure and show the capabilities of the proposed approach.

**Keywords**: Reconfiguration, Manufacturing System, Resilience

## 1.Introduction

Resilience is the capability of a system to absorb major disruptions and rapidly recover its functionality by properly adjusting and responding to such perturbations (Hosseini *et al.*, 2016; Hollnagel, 2006). As a consequence, in order to allow quantification of resilience, it is common practice to refer to the time trend of functionality in the aftermath of the disruption (occurring at time $t_0$) and during the recovery period from $t_d$ to $t_r$ as shown in Fig. 1.

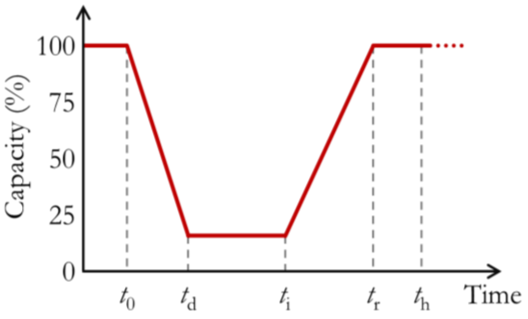

**Figure 1: Capacity evolution over time**

Provided that the actual trend of the capacity as a function of time $C(t)$ can be estimated, it is possible to assess the resilience over a conventional period $t_0$ to $t_h$ according to Eq. (1) (Bruneau *et al.*, 2003; Cimellaro *et al.*, 2009).

$$\text{Resilience} = \frac{1}{t_h - t_0}\int_{t_0}^{t_h} C(t)dt \tag{1}$$

Therefore, knowledge of the $C(t)$ curve is a key factor in resilience assessment. When the disruption causes physical damage to the plant and its equipment, i.e., a major accident or a natural hazard triggering a NaTech event such as a flood or an earthquake, the $C(t)$ curve results from the scheduling of plant reconstruction activities, and models to build the capacity time trend according to the process configuration are available (Caputo *et al.*, 2023). However, major disruptions may also include generic unforeseen events that may seriously hinder normal operations, such as supply chain interruptions caused by pandemics, wars, main supplier failures as well as significant changes in market demand. Such disruptions might necessitate the redesign of manufacturing systems to accommodate alternative input materials or the switch to new products manufacture to fulfill the needs of changing markets. In such cases the capacity recovery does not imply reconstruction of a damaged process but the reconfiguration to a totally new one. An example is given by the suppliers base of traditional automotive manufacturers who must adapt to the switch from the manufacture of internal combustion engine vehicles to electric ones. Alexopoulos *et al.* (2022) instead describe the case of a manufacturer of automotive components, adopting additive manufacturing (3D printing) or injection molding processes, forced to switch to medical respirator manufacture owing to the COVID-19 pandemic outbreak. Given the constant change in the global manufacturing landscape, with consumer preferences rapidly varying (Koren *et al.*, 2018; Maganha *et al.*, 2018), new technologies arising at a fast pace (Napoleone *et al.*, 2018), and unexpected disruptions interrupting entire supply chains (Zidi *et al.*, 2023), classic manufacturing processes designed for rigidity and efficiency in single-product production are becoming increasingly inflexible and unresponsive. The reconfiguration of manufacturing systems can be viewed as a strategy for resilience enhancement, as it allows companies to adapt to unexpected events and maintain operations. In the literature, the research on the reconfiguration of production systems has been traditionally focused on Reconfigurable Manufacturing Systems (RMSs) which provide an attractive option by allowing firms to adapt their production capabilities to meet changing demands (Beauville Dit Eynaud *et al.*, 2022; Kjeldgaard *et al.*, 2023). A RMS is a manufacturing system that has been specifically designed to be easily and periodically adapted to changing production requirements. Unlike traditional systems that are frequently designed for a single product or product line, RMSs are modular, allowing individual components to be reorganized or replaced. This modularity creates a system that can be readily scaled up or down, modified to generate other goods, or upgraded with new technology. However, the above assumptions do not hold in the case of a traditional manufacturing system reconfiguration. Moreover, while the literature on RMS is quite ample (Yelles-Chaouche *et al.*, 2021; Bortolini *et al.*, 2018; Koren *et al.*, 2018; Mehrabi *et al.*, 2002; Mehrabi *et al.*, 2000), existing research on reconfiguration cost estimation is limited, thus asking for novel methods dedicated to resilience enhancement purposes. Spicer and Carlo (2007), proposed a model to calculate the reconfiguration cost between two configurations. The model considers various factors including labor, lost capacity, and investment/salvage costs. The reconfiguration time is calculated based on the number of man-hours required for layout changes. Deif and ElMaraghy (2007), focused on capacity scalability in RMSs. The proposed approach conceptually defines a total reconfiguration cost as the sum of the cost of capacity change, the cost of lost production during system reconfiguration outages, and the cost of installation and configuration change, but does not provide an explicit modeling of these costs. Chen Jie *et al.* (2009), proposed a method for modeling reconfiguration costs using the Petri Net approach. This approach utilizes a conjunction matrix to describe the production process and highlights the differences between the process sets before and after reconfiguration. Based on these differences, the Authors only consider equipment installation and decommissioning costs, but neglect to include reconfiguration time into the model. Kuzgunkaya and ElMaraghy (2009), considered the duration of reconfiguration time in terms of man-hours calculated as a function of the number of bases and modules to be installed or uninstalled and accordingly calculated a reconfiguration cost by multiplying the hourly labor cost by the man-hours of labor required. The model assigns a constant time for installing/uninstalling bases and modules, which may not reflect real-world variations in complexity. The problem of process reconfiguration in the context of plant resilience has been instead considered by Alexopoulos *et al.* (2022). They proposed a "Penalty of change" (POC) method for the resilience assessment by calculating the cost of adapting to potential disruptions and considering the loss of profit due to inadequate production capacity as a result of changes in market demand while reconfiguring the system. Nevertheless, POC method relies on subjective estimations of potential disruptions and their probabilities, which can be a source of error, and neglects the physical configuration changes to be performed. Additionally, their model assumes discrete periods for disruptions, which might not always be realistic. More importantly, they do not provide a method to explicitly compute the time and cost of reconfiguration. Huang *et al.* (2024), addressed a critical challenge in manufacturing: efficiently designing and configuring RMS under uncertain demand fluctuations. The proposed method considers the investment and installation costs of individual functional modules to be installed on the bases. Nevertheless, the study assumes a fixed basis for part-family formation, focusing on configuration optimization based on the families and types of parts to be processed.

Overall, a time and cost-based reconfiguration model for manufacturing systems is not yet available, and its development is the objective of this paper. Overall, while building on earlier research about RMS, this paper has a different perspective, as it does not consider manufacturing systems conceived with a modular structure for periodic reconfiguration, but aims to estimate the duration and cost of the reconfiguration of generic manufacturing systems, based on their actual structure and the mutual constraints between reconfiguration tasks, in the context of resilience engineering, where reconfiguration is dictated by a major disruption in market conditions. In so doing the proposed model extends the functionality of earlier resilience models focusing only on recovering capacity lost by physical disruptions (Caputo *et al.*, 2023).

Based on the problem statements discussed above, the main question for this study is:

How can we estimate the duration and cost required to reconfigure a traditional manufacturing system in response to a significant disruption, such as a shift in market conditions or an interruption in the supply chain?

Apart from the capital and operating costs involved with reconfiguration procedures the model also accounts for the opportunity cost of lost production. Finally, this model enables firms to measure their facilities' resilience to market shifts or supplier disruptions, resulting in a clear picture of the economic impact of reconfiguration actions.

## 2.Reconfiguration duration and capacity curve estimation

For sake of brevity, we assume that the future system is conceived to produce a single product, which is called New Product. We also assume that pieces of equipment may be connected by material handling systems, either fixed or manual, and only the former may need to be reconfigured. The first step is to identify the types of different equipment utilized in the current manufacturing systems, and those needed in the reconfigured system. Then two vectors WS are defined, with a length equal to N, and represent the set union of the types of machines that compose the current (AsIs) and the future system (ToBe). Each element in the vector represents a machine type and it is individuated by the index *i*, which ranges from 1 to N. $\mathrm{WS}_{\mathrm{AsIs}}$ is an array that represents the number of machines of type *i* of the current systems, whereas $\mathrm{WS}_{\mathrm{ToBe}}$ refers to the system after the reconfiguration. ΔWS is defined as follows (Eq. 2), and it represents the number of machines of type *i* that should be purchased, if there is a positive value, or dismantled otherwise.

$$\Delta\mathrm{WS} = \mathrm{WS}_{\mathrm{ToBe}} - \mathrm{WS}_{\mathrm{AsIs}} \tag{2}$$

For each of the equipment involved in the reconfiguration process, one or more of the following activities may be required (ordering to the manufacturer, dismantling, relocation, installation, connection between equipment and material handling system). To determine the reconfiguration time, and the capacity-time curve, the full list of reconfiguration activities, their duration, and the precedence constraints must be compiled. Being A the number of above tasks to be carried out, an A×A array AC may be used to represent precedence constraints. In the generic i-j cell if an activity in row *i*-th cannot be executed until another activity in column *j*-th has been completed, is indicated by a value of 1. Alternatively, a value of 0 is placed. Consequently, the rows where no 1 appears correspond to activities that can be independently performed since they have no predecessors. A discrete timeline is established to mark the initiation of reconfiguration operations, with $\mathrm{T}_0$ indicating the starting point. For a generic *i*-th activity the completion date $\mathrm{T}_{\mathrm{E}i}$ is the start date $\mathrm{T}_{\mathrm{S}i}$ plus the activity duration $\mathrm{D}_i$.

$$\mathrm{T}_{\mathrm{E}_i} = \mathrm{T}_{\mathrm{S}_i} + \mathrm{D}_i \tag{3}$$

At $\mathrm{T}_0$ the activities having no predecessors are started, and their completion date is computed resorting to Eq. (3). The delivery lead time (LT) depends on the number of new items that need to be installed and is communicated by the supplier at the time of the machine purchase. $\mathrm{TLT}_{\mathrm{WS}}$ indicates the total delivery lead time array for each *i* machine (Eq. 4).

$$\mathrm{TLT}_{\mathrm{WS}} = \begin{cases} \text{if } \Delta\mathrm{WS}_i \le 0 : 0 \\ \text{else} : \mathrm{LT}_{\mathrm{WS}_i} \end{cases} \tag{4}$$

And $\mathrm{TLT}_{\mathrm{TS}}$ indicates the total lead time array for *ij* transport system (Eq. 5). In which the symbols "Λ" and "V" represent the Boolean logical operators "AND" and "OR", respectively.

$$\mathrm{TLT}_{\mathrm{TS}} = \begin{cases} \text{if } \left(\Delta\mathrm{TS}_{ij} = -1 \vee -2\right) \wedge \mathrm{TS}_{\mathrm{AsIs}_{ij}} = 1 : \\ \qquad \mathrm{TLT}_{\mathrm{TS}_{ij}} = \mathrm{LT}_{\mathrm{TS}_{ij}} \\ \text{else} : \mathrm{TLT}_{\mathrm{TS}_{ij}} = 0 \end{cases} \tag{5}$$

Typically, the issuance of purchase orders for new machines is considered the start of the timeline, as it allows for the performance of other activities, such as equipment relocation or decommissioning, while further activities may be delayed until the delivery of the new machines. As soon as an activity is completed the 1 value in the corresponding column of the above array is switched to 0, and the matrix is inspected again to identify whether further activities become executable as a consequence of the elimination of precedence constraints. When a task becomes executable its starting date is recorded and the completion date is computed, proceeding iteratively until all activities are executed. As time progresses, each completed activity will be recorded in a list of events sorted by their occurrence in ascending order, which will be updated dynamically. When the last activity pertaining to a given equipment is completed, the state variable corresponding to that equipment is switched from 0 to 1. This allows us to determine the impact of each equipment installation on the capacity recovery of the process flow, according to the procedure described by Caputo *et al.* (2023) thus allowing us to build the time-dependent capacity curve *C*(*t*). However, in most cases, as the one considered in this paper's numerical example, the equipment of a process flow are logically connected in series, meaning that capacity can be utilized only after all the equipment have been installed. In this case *C*(*t*) = 0 during the entire reconfiguration period, which starts at $\mathrm{T}_0$ and terminates when the last activity related to the last equipment installed is completed. From the end date of capacity reconfiguration, a ramp-up period begins, during which the nominal installed capacity becomes gradually utilizable in a linear manner until it reaches its full-scale value.

## 3.Reconfiguration costs estimation

The dismantling of machines could generate an income due to the selling of those that have a residual value. On the other hand, the purchasing of new machines represents a cost. We can define the reconfiguration cost (CR) function by considering the following items:

$$\mathrm{CR}_{\mathrm{WS}} = \mathrm{CF}_{\mathrm{WS}} + \mathrm{IC}_{\mathrm{WS}} + \mathrm{DC}_{\mathrm{WS}} + \mathrm{MC}_{\mathrm{WS}} \tag{6}$$

where $\mathrm{CF}_{\mathrm{WS}}$ is the cash flow from the purchase or sale of machine, $\mathrm{IC}_{\mathrm{WS}}$ is the installation costs, $\mathrm{DC}_{\mathrm{WS}}$ indicates the dismantling and decommissioning costs of unnecessary machines, and $\mathrm{MC}_{\mathrm{WS}}$ is the relocation costs of machines. In particular, the $\mathrm{CF}_{\mathrm{WS}}$ can be defined using Eq. (7), and it can assume a positive value in the case of the purchase of a machine, or a negative value arising from the revenue from the sale of a machine.

$$\mathrm{CF}_{\mathrm{WS}} = \sum_{i=1}^{\mathrm{N}} \begin{cases} \text{if } \Delta\mathrm{WS}_i < 0 : \Delta\mathrm{WS}_i \cdot \mathrm{C}_{\mathrm{WSBF}_i} \cdot \left(1 - \dfrac{\mathrm{L}_{\mathrm{WS}_i}}{\mathrm{ML}_{\mathrm{WS}_i}}\right) = \mathrm{RD}_{\mathrm{WS}} \\ \text{if } \Delta\mathrm{WS}_i \geq 0 : \left(\Delta\mathrm{WS}_i \cdot \mathrm{C}_{\mathrm{WSBF}_i}\right) = \mathrm{I}_{\mathrm{WS}_i} \end{cases} \quad (7)$$

where $I_{WS}$ denotes machine investment costs, which includes the purchase and transportation of the new machines. If the *i*-value in the array ΔWS is negative, the corresponding number of machines will be dismantled and sold at their residual value ($RD_{WS}$). The residual value can be assessed as the multiplication of the purchase cost ($C_{WSBF}$) and the ratio between the amount of time that the machine has been used and the expected machine life ($ML_{WS}$), in which the machine’s service life can be evaluated as the difference between $ML_{WS}$ and the machine’s utilized life (with $L_{WS} \leq ML_{WS}$). In addition, this value can be adjusted to account for the difference with the machine’s book value. However, if the *i*-value in the array ΔWS is positive, that number of machines of that type will be purchased. That means that the expenditure can be calculated by multiplying the number of machines and their price. Finally, if $\Delta WS_i$ is equal to 0, there is no cash flow for the *i*-th type machine since it does not need to be bought nor sold.

The installation cost (Eq. 8) of machine type *i* is greater than 0 only if $\Delta WS_i$ is higher than 0, and it is assessed by multiplying the number of *i* machines, the installation time ($IT_{WS}$) evaluated in days per machine per worker, and the daily workers cost, evaluated with the hourly cost of workers employed ($C_{HW}$) and the daily work hours (HS).

$$\mathrm{IC}_{\mathrm{WS}} = \sum_{i=1}^{\mathrm{N}} \begin{cases} \text{if } \Delta\mathrm{WS}_i \leq 0 : 0 \\ \text{if } \Delta\mathrm{WS}_i > 0 : \Delta\mathrm{WS}_i \cdot \mathrm{IT}_{\mathrm{WS}_i} \cdot \mathrm{C}_{\mathrm{HW}} \cdot \mathrm{HS} \end{cases} \quad (8)$$

The same procedure is conducted for the dismantling cost $DC_{WS}$ (Eq. 9), where $DC_{WS} > 0$ if $\Delta WS_i < 0$, where $DT_{WS}$ denotes the dismantling time.

$$\mathrm{DC}_{\mathrm{WS}} = \sum_{i=1}^{\mathrm{N}} \begin{cases} \text{if } \Delta\mathrm{WS}_i \geq 0 : 0 \\ \text{if } \Delta\mathrm{WS}_i < 0 : \left|\Delta\mathrm{WS}_i \cdot \mathrm{DT}_{\mathrm{WS}_i} \cdot \mathrm{C}_{\mathrm{HW}} \cdot \mathrm{HS}\right| \end{cases} \quad (9)$$

Machines included in both the AsIs and ToBe systems can be moved to achieve a new layout for the new system. The array $M_{WS}$ is used to indicate if it is necessary to move the machines of type *i*. It is a binary array, in which 1 means move, and 0 no move. The relocation generates a cost ($MC_{WS}$) proportional to the number of machines to be moved, the relocation operation duration ($MT_{WS}$), and the cost of workers (Eq. 10).

$$\mathrm{MC}_{\mathrm{WS}} = \sum_{i=1}^{\mathrm{N}} \begin{cases} \text{if } \Delta\mathrm{WS}_i \geq 0 : \\ \mathrm{MS}_{\mathrm{WS}_i} \cdot \left(\mathrm{WS}_{\mathrm{ToBe}_i} - \left|\Delta\mathrm{WS}_i\right|\right) \cdot \mathrm{MT}_{\mathrm{WS}_i} \cdot \mathrm{C}_{\mathrm{HW}} \cdot \mathrm{HS} \\ \text{if } \Delta\mathrm{WS}_i < 0 : \mathrm{MS}_{\mathrm{WS}_i} \cdot \mathrm{WS}_{\mathrm{ToBe}_i} \cdot \mathrm{MT}_{\mathrm{WS}_i} \cdot \mathrm{C}_{\mathrm{HW}} \cdot \mathrm{HS} \end{cases} \quad (10)$$

A similar analysis can be made for transportation systems. An N×N Transportation System matrix can be defined for both the current ($TS_{AsIs}$) and future ($TS_{ToBe}$) systems, where the *i*-th row indicates the flow departure equipment and the *j*-th column is the destination equipment. The value of the *i-j* cell indicates whether no flows exist between machines *i* and *j* (0) or a fixed transportation system (1) or a manual one (2) is used. The difference between the two matrices indicates the required changes in the TS configuration (Eq. 11).

$$\Delta\mathrm{TS} = \mathrm{TS}_{\mathrm{ToBe}} - \mathrm{TS}_{\mathrm{AsIs}} \quad (11)$$

Similarly to Eq. (6), we can evaluate the cost function related to transportation systems (TS), as follows (Eq. 12):

$$\mathrm{CR}_{\mathrm{TS}} = \mathrm{CF}_{\mathrm{TS}} + \mathrm{IC}_{\mathrm{TS}} + \mathrm{DC}_{\mathrm{TS}} + \mathrm{MC}_{\mathrm{TS}} \quad (12)$$

where $CF_{TS}$ is the transport system cash flow, $IC_{TS}$ is the installation costs, $DC_{TS}$ indicates the dismantling and decommissioning costs, and $MC_{TS}$ the moving costs. It is assumed that the cash flows related to the changes in the transport systems (Eq. 13) are equal only to the purchase cost of the new transport system.

$$\mathrm{CF}_{\mathrm{TS}} = \sum_{i=1}^{\mathrm{N}} \sum_{j=1}^{\mathrm{N}} \begin{cases} \text{if } \left(\Delta\mathrm{TS}_{ij} = 1 \vee -1\right) \wedge \mathrm{TS}_{\mathrm{ToBe}_{ij}} = 1 : \mathrm{I}_{\mathrm{TS}_{ij}} \\ \text{else} : 0 \end{cases} \quad (13)$$

where $I_{TS}$ denotes the array of transport system investment costs. Additionally, there is the cost of the installation of the new transport systems (Eq. 14) and dismantling and decommissioning of the unnecessary ones (Eq. 15). These last two are evaluated in a similar manner as the machines.

$$\mathrm{IC}_{\mathrm{TS}} = \sum_{i=1}^{\mathrm{N}} \sum_{j=1}^{\mathrm{N}} \begin{cases} \text{if } \left(\Delta\mathrm{TS}_{ij} = 1 \vee -1\right) \wedge \mathrm{TS}_{\mathrm{ToBe}_{ij}} = 1 : \\ \mathrm{IT}_{\mathrm{TS}_{ij}} \cdot \mathrm{C}_{\mathrm{HW}} \cdot \mathrm{HS} \\ \text{else} : 0 \end{cases} \quad (14)$$

$$\mathrm{DC}_{\mathrm{TS}} = \sum_{i=1}^{\mathrm{N}} \sum_{j=1}^{\mathrm{N}} \begin{cases} \text{if } \left(\Delta\mathrm{TS}_{ij} = -1 \vee -2\right) \wedge \mathrm{TS}_{\mathrm{AsIs}_{ij}} = 1 : \\ \mathrm{DT}_{\mathrm{TS}_{ij}} \cdot \mathrm{C}_{\mathrm{HW}} \cdot \mathrm{HS} \\ \text{else} : 0 \end{cases} \quad (15)$$

The total reconfiguration cost (CR) is given by (Eq. 16):

$$\mathrm{CR} = \mathrm{CR}_{\mathrm{WS}} + \mathrm{CR}_{\mathrm{TS}} \quad (16)$$

Another cost to consider is the lost production opportunity cost during the reconfiguration process for both the old and new products. Here we assume that the demand for the new product ($D_{NP}$) has a linear growth as represented by Eq. (17).

$$\mathrm{D}_{\mathrm{NP}}(t) = \begin{cases} \text{if } \mathrm{D}_{\mathrm{NP}}(t) < \mathrm{CP} : \mathrm{D}_0 + b \cdot t \\ \text{if } \mathrm{D}_{\mathrm{NP}}(t) \geq \mathrm{CP} : \mathrm{CP} \end{cases} \quad (17)$$

The demand is assumed to be the one the system can respond to; thus, its growth stops at the rated production capacity (CP). Therefore, since the production capacity and the demand change over time, the lost revenue opportunity cost ($C_{NLP}$) can be calculated according to Eq.

(18). The lost demand is dependent on the reconfiguration duration (TR) and the ramp-up period duration (RT). Indeed, the production capacity increases over time until it reaches the installed capacity.

$$C_{NLP} = \int_{0}^{TR+RT} D_{NP}(t) - CP(t)dt \cdot CM_{NP} \qquad (18)$$

## 4.Numerical application

In this application example, we consider a manufacturing system schematized as depicted in Fig. 2. The current numerical application assumes that from the first activity, the current system stops working.

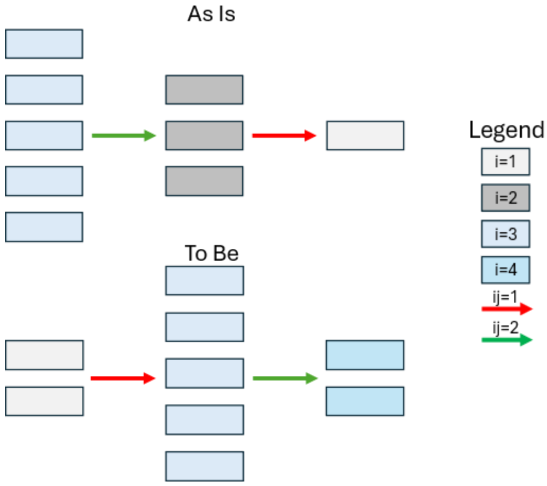

**Figure 2: Scheme of current and reconfigured systems**

Additionally, since the types of machines are arranged serially, the new system starts production when the whole reconfiguration process is over. Finally, the ramp-up period is set to 30 days. Looking at the AsIs and ToBe configuration the length of the arrays WS is equal to 4 since there are four different types of machines (i=1…4). Additionally, the red arcs represent the fixed transport systems, whereas the green ones are the manual ones. It can be observed that three machines of type 2 will be dismantled, and two machines of type 4 will be purchased. The machines of types 1 and 3 will be moved to achieve the new layout. From the fixed transport systems point of view, the type 2, and 3 conveyors will be dismantled, while the type 1, and 3 will be bought.

Table 1 provides some relevant data about the cost and duration of the activities related to the reconfiguration of the system, whereas Table 2 refers to the machines available in the AsIs configuration.

**Table 1: Cost and duration of some reconfiguration activities**

| Unit | Index | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| €/machine | $C_{WS}$ | 10000 | 20000 | 5000 | 10000 |
| day/machine | $LT_{WS}$ | 100 | 45 | 90 | 130 |
| day/machine worker | $IT_{WS}$ | 15 | 20 | 10 | 10 |

**Table 2: Data about the activities related to machines available in the AsIs configuration of the system**

| Unit | Index | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| day | $L_{WS}$ | 730 | 365 | 1095 | 0 |
| €/machine | $C_{WBF}$ | 10000 | 20000 | 5000 | 0 |
| day/machine worker | $DT_{WS}$ | 10 | 5 | 5 | 0 |
| day | $ML_{WS}$ | 3650 | 3650 | 3650 | 0 |

Below there are the values of the involved WS vectors and TS matrices:

$$\begin{aligned} WS_{AsIs} &= \begin{bmatrix}1 & 3 & 5 & 0\end{bmatrix} \\ WS_{ToBe} &= \begin{bmatrix}2 & 0 & 5 & 2\end{bmatrix} \end{aligned} \quad \rightarrow \quad \Delta WS = \begin{bmatrix}1 & -3 & 0 & 2\end{bmatrix}$$

$$\begin{aligned} TS_{AsIs} &= \begin{bmatrix}0 & 0 & 0 & 0\\ 1 & 0 & 0 & 0\\ 0 & 2 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix} \\ TS_{ToBe} &= \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 2\\ 0 & 0 & 0 & 0\end{bmatrix} \end{aligned} \quad \rightarrow \quad \Delta TS = \begin{bmatrix}0 & 0 & 1 & 0\\ -1 & 0 & 0 & 0\\ 0 & -2 & 0 & 2\\ 0 & 0 & 0 & 0\end{bmatrix}$$

For the sake of simplicity, the dismantling, installing, and lead time of the fixed transport systems are considered the same for each hypothetical transport item in the system, and equal to the values resumed in Table 3. The same assumption was made for the purchasing cost.

**Table 3: Transport systems data**

| Unit | Symbol | Value |
|---|---|---|
| day/worker | $DT_{TS}$ | 10 |
| day/worker | $IT_{TS}$ | 10 |
| day | $LT_{TS}$ | 60 |
| € | $I_{TS}$ | 10000 |

Other relevant data is reported in Table 4.

**Table 4: Other relevant data**

| Unit | Symbol | Value |
|---|---|---|
| €/h | $C_{HW}$ | 50 |
| [-] | $N_W$ | 5 |
| h/day | HS | 8 |
| day | RT | 30 |
| pz | $D_0$ | 200 |
| pz/day | b | 2 |
| €/pz | $MC_{NP}$ | 2 |

Finally, Table 5 shows the activity types, the machines of interest, and their durations.

**Table 5: Activities data**

| ID | Activity | Machine | Duration |
|---|---|---|---|
| 1 | Lead time | 1 | 100 |
| 2 | Lead time | 4 | 130 |
| 3 | Install | 1 | 3 |
| 4 | Install | 4 | 2 |
| 5 | Install | 4 | 2 |
| 6 | Move | 1 | 0.4 |
| 7 | Move | 3 | 0.8 |
| 8 | Move | 3 | 0.8 |
| 9 | Move | 3 | 0.8 |
| 10 | Move | 3 | 0.8 |
| 11 | Move | 3 | 0.8 |
| 12 | Dismantle | 2 | 1 |
| 13 | Dismantle | 2 | 1 |
| 14 | Dismantle | 2 | 1 |
| 15 | Lead time | 5 | 60 |
| 16 | Install | 5 | 2 |
| 17 | Dismantle | 5 | 2 |

Starting from the data collected in Table 5 and the priority constraints, which are not reported for brevity reasons, the duration of the whole reconfiguration process of 143.3 days was assessed. Please note that this duration can be reduced by increasing the number of workers dedicated to the reconfiguration activities. It is also possible to shorten this duration by starting the first dismantling operation to shadow the lead times of the ordered machines and transport systems. In that case, the first activity is number 12, which could start 127 days from the release of the orders, instead of at the same time of the orders' release; therefore, the actual time of reconfiguration is equal to 16.4 days. Considering that the delivery lead times of machines are not shadowed, the full capacity is recovered 173.4 days after the release of the orders.

Figure 3 shows the trend of the demand, the lost production, and the capacity of the system over time.

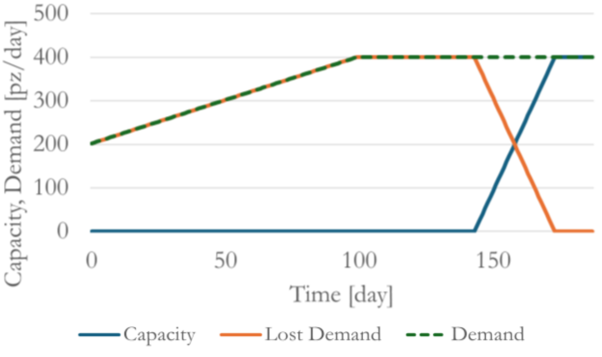

**Figure 3: System capacity, product demand, and lost demand over time**

The total lost demand during the reconfiguration process is calculated as 53500 pieces, which corresponds to 107000 € of lost production cost, resulting in a total cost $C_{TOT}$, evaluated by the sum of CR and $C_{NLP}$ of 122800 €.

**Table 6: Estimated costs and cash flows**

| Cost item | Value [€] |
|---|---|
| $I_{WS}$ | 30000 |
| $RD_{WS}$ | 54000 |
| $CF_{WS}$ | 24000 |
| $IC_{WS}$ | 14000 |
| $DC_{WS}$ | 6000 |
| $MC_{WS}$ | 8800 |
| $CF_{TS}$ | 10000 |
| $IC_{TS}$ | 500 |
| $DC_{TS}$ | 500 |
| CR | 15800 |
| $C_{NLP}$ | 107000 |
| $C_{TOT}$ | 122800 |

Table 6 reports the cost of the reconfiguration process.

The resilience index, calculated according to Eq. (1) and considering a $t_h$ equal to 200 days, is 0.21. This value is based only on the capacity curve related to the production of the new product (Figure 3).

## 5.Conclusions

In the present study, a novel model for assessing the duration and economic implications of reconfiguring manufacturing facilities in response to market fluctuations or supply chain disruptions has been proposed. The model is designed to determine the capital and operational expenses involved in the reconfiguration process, as well as the time required for restoring production capacity. To this end, the model takes into account the time course of capacity reconfiguration based on the existing process structure and sequence constraints dictated by reconfiguration tasks. This approach enables the quantification of lost production costs and reconfiguration duration, thereby facilitating companies to assess the resilience of their production facilities to market changes. By providing a clear and concise picture of the economic impact of reconfiguration efforts, the proposed model empowers companies to make decisions about implementing reconfigurations in production systems. The proposed model contributes significantly to the existing body of research on reconfigurable system design and resilience assessment by providing a comprehensive framework for estimating reconfiguration costs and duration. Its effectiveness can be ascertained by its ability to provide a holistic view of the economic implications of reconfiguration efforts, thus enabling companies to make informed decisions. The model can be a valuable tool for decision-makers in manufacturing industries. By quantifying the costs and duration of reconfiguration processes, the model enables companies to assess the economic feasibility of different reconfiguration strategies and prepare contingency plans for expected market changes. This information can guide decision-makers in selecting the most cost-effective and time-efficient approach to adapt to disruptions and maintain operational continuity, as well as perform risk assessment studies. The model also allows to perform sensitivity analyses about the impact of uncertain variables such as cost and activity durations.

Future work will integrate the proposed approach with existing approaches for estimating resilience from physical disruptions in order to introduce a comprehensive model for evaluating the resilience of production facilities.

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## Appendix A. NOMENCLATURE

| Symbol | Measurement unit | Meaning |
|---|---|---|
| AC | [-] | Matrix of the activities sequence constraints |
| $C_{HW}$ | [€/h] | Hourly cost of workers |
| $C_{NLP}$ | [€] | Cost of new product lost production |
| $C_{TSBF}$ | [€] | Array of transport systems investment cost made before reconfiguration |
| $C_{WS}$ | [€] | Array of machines investment cost |
| $C_{WSBF}$ | [€] | Array of machine investment costs made before reconfiguration |
| $CF_{WS}$ | [€] | Cash flow machines |
| $CF_{TS}$ | [€] | Cash flow transport systems |
| $CM_{NP}$ | [€/pz] | Contribution margin of new product |
| CP | [pz] | Production capacity |
| CR | [€] | Total cost for reconfiguration |
| $DC_{TS}$ | [€] | Dismantling and decommissioning costs of machines |
| $DC_{WS}$ | [€] | Dismantling and decommissioning costs of machines |
| $D_{NP}$ | [pz] | Demand for the new product |
| $DT_{TS}$ | [day/machine worker] | Dismantling time of machines |
| $DT_{WS}$ | [day/machine worker] | Array of dismantling time of machines |
| HS | [h/day] | Daily work hour |
| $I_{WS}$ | [€] | Investment cost of machines |
| $I_{TS}$ | [€] | Array of transport systems investment cost |
| $IC_{TS}$ | [€] | Installation cost of transport systems |
| $IC_{WS}$ | [€] | Installation cost of machines |
| $IT_{TS}$ | [day/machine worker] | Installation time of transport systems |
| $IT_{WS}$ | [day/machine worker] | Array of installation time of machines |
| $IT_{WS}$ | [day/machine worker] | Installation time of machines |
| $L_{TS}$ | [day] from date now | Array of installation date of transport systems |
| $LT_{TS}$ | [day] | Array of lead time of transport systems |
| $LT_{WS}$ | [day] | Array of lead time of machines |
| $L_{WS}$ | [day] from date now | Array of installation date of machines |
| $MC_{TS}$ | [€] | Moving cost of transport systems |
| $MC_{WS}$ | [€] | Moving cost of machines |
| $ML_{WS}$ | [day] | Array of machines' life |
| $MT_{TS}$ | [day/machine worker] | Moving time of transport systems |
| $MT_{WS}$ | [day/machine worker] | Moving time of machines |
| $M_{WS}$ | [-] | Binary array of moving necessity of machines |
| $N_{W}$ | [-] | Number of workers |
| $RD_{WS}$ | [€] | Revenue from selling the dismantled machines |
| RT | [day] | Ramp up time |
| $TLT_{TS}$ | [day] | Array of total lead time of transport systems |
| $TLT_{WS}$ | [day] | Array of total lead time of machines |
| TPV | [pz] | Theoretical production volume |
| TR | [day/worker] | Total time for reconfiguration |
| $TS_{AsIS}$ | [-] | Matrix of the presence and type of transport systems between the machines before reconfiguration (from-to) |
| $TS_{ToBE}$ | [-] | Matrix of the presence and type of transport systems between the machines after reconfiguration (from-to) |
| $WS_{AsIs}$ | [-] | Array of machines before reconfiguration |
| $WS_{ToBe}$ | [-] | Array of machines after reconfiguration |
| $\Delta WS$ | [-] | Difference between $WS_{ToBe\ and}$ $WS_{AsIs}$ |
| $\Delta TS$ | [-] | Difference between $TS_{ToBe}$ and $TS_{AsIs}$ |