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Optimizing of the Convertibility of Reconfigurable Manufacturing Systems [★]

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Abstract: One of the most topical issues of sustainable development is extending the life cycle of production systems. Reconfigurable manufacturing system (RMS) aims to adapt efficiently to the rapidly changing market. One lever to extend the life cycle of RMS is the ability to quickly adapt to a new product (called convertibility). In this article, we present a model for the design of RMS, optimizing both its convertibility to prolongate its life cycle, and its cost to remain competitive. The convertibility is assessed on three axes: the choice of machines, the choice of transportation systems, and the physical configuration of the machines in the plant and their connection. We formalize this problem and model it by a bi-objective mixed-integer linear program. We illustrate our approach on an example.

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Keywords: Reconfigurable manufacturing systems, Line design and balancing, Sustainable manufacturing.

1. INTRODUCTION

The concept of Reconfigurable Manufacturing System (RMS) was introduced by Dr. Koren in 1999 to respond to rapid market changes (Koren et al., 1999). These systems rely on reconfigurable machines that can be easily added, removed or adjusted - by modifying the hardware or reprogramming the software - to adapt to variations in demand. RMSs aim to provide an alternative to dedicated manufacturing systems (DMS), which are highly productive but not flexible, and flexible manufacturing systems (FMS), which are expensive and have low productivity. Therefore, they offer a level of flexibility to produce a family of products, keeping high productivity. A review of RMSs can be found in (Pansare et al., 2023).

Battaïa et al. (2020) discuss how the characteristics of RMS can be applied to develop sustainable and energy-efficient manufacturing systems. In particular, the convertibility of RMS, i.e. its ability to integrate new products, is linked to the life cycle of the system. Koren (2010) defines convertibility as the ability to easily change the functionality of the existing system and machines to meet new market requirements. Indeed, a more convertible system will sustain more changes in the specifications of the products, delaying the moment when the re-design of the system is needed, and thus the duration of use of the machines. However, the configurations and resources allowing such a convertibility are often more expensive, either in investment or operations.

The first measure of the convertibility of the system was introduced by Maier-Sperdelozzi et al. (2003). The convertibility measure is a weighted sum of three components, focusing on the convertibility of configuration, machine,

and material handling. To assess the convertibility of configuration featuring identical machines at each station, the authors propose the mathematical approach based on (i) the minimum increment of conversion, (ii) the width of the system and (iii) the number of connections between machines. As for the convertibility of machines and material handling, the authors operate on the assumption that certain machines/material handling possess inherent features and characteristics that make them more convertible. The authors propose a questionnaire in which each answer gives its own assessment of convertibility based on these features and characteristics.

Lafou et al. (2014) provide a convertibility indicator for manual mixed-model assembly lines by adapting the model of Maier-Sperdelozzi et al. (2003). The authors introduce two new components. The first component concerns the consideration of different products on the same line in the convertibility of the configuration. The second component concerns the addition of a fourth term to take into account product family convertibility.

Chinnathai et al. (2017) define system convertibility as an average of equipment convertibility and layout convertibility each of which has its own weight. In the article, equipment convertibility is the function of the convertibility of each assembly sub-system, where a sub-system represents either workstations or material handling units. The layout convertibility is the average of the indices describing various aspects of the system, such as autonomy, connectivity and replication index. The authors decompose automated assembly systems into individual components, and an assessment is conducted to understand their impact on the system's adaptability.

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Previous works describe measures of the convertibility of the system. However there are no works that would take into account the convertibility of the system simultaneously with other factors such as cost of the RMS from the design phase. This is the gap to be filled in this paper.

Our goal is to propose a measure which calculate the convertibility of the system taking into account the cost at the design phase. We propose an approach of bi-objectif optimization of the convertibility and the investment cost. Two main developments are presented in this article. Firstly, in Section 2, we propose an adaptation of a measure to assess the convertibility of a system producing different models of a same product family, during the design phase. Then, in Section 3, we formalize the problem of designing a RMS optimizing the convertibility and the cost, while satisfying the demand, as a Mixed-Integer Linear Programming (MILP). The numerical experiments are presented in Section 4. Finally, Section 5 concludes this paper and discusses the perspectives.

2. PROBLEM DESCRIPTION

We consider a reconfigurable manufacturing system as a parallel-serial line with crossovers, as presented in (Freiheit et al., 2004). The system is composed of several stations. The necessary operations for the production are partitioned on these stations, and the product is processed successively on each of them. Each station is composed of one or several production resources, which we will denominate as machines in this paper. Transportation devices are used between the machines of the different stations to transport the product throughout the system.

We suppose that the line balancing of the system was done in a previous phase, taking into account the production constraints (precedence, inclusion, exclusion) for all products of the family. Thus we considered that the assignment of operations to stations $\mathcal{S} = \{1, \dots, S_{\max}\}$ is known, and is the same for all machines for a same station. This assumption is inspired from industrial case studies on related research works. One of them is (Malyutin, 2016) which considered an engine assembly line design at Mercedes Benz in Germany, aiming to minimize the number of workers knowing the line balancing.

We aim to optimize the investment cost and the three components of the convertibility measure proposed by (Maier-Sperdelozzi et al., 2003), associated with the configuration, machine and transportation of material. The main difference is that our goal is not to measure the convertibility of an existing system, but to create a tool that helps to choose the optimal system in terms of cost and convertibility. Thus, in our approach, the number of machines, transport and connections is not known in advance so we use linearized measures in the problem. Our problem is composed of three main decisions:

- the type of machines to use at each station,
- the type of transport devices to use between the stations,
- the number of connections between the machines existing in the system (varying from a fully parallel structure, to a fully crossover one, through hybrid intermediates).

2.1 Machine selection and convertibility

In this study, we suppose that I different types of machines are available (forming the set $\mathcal{I} = \{1, \dots, I\}$). We suppose that a station can be implemented with only one type of machines. Knowing the assignment of operations to stations and the specification of each type of machines regarding the productivity, we define $N_{i,s}$ the number of machines of type $i \in \mathcal{I}$ that are required on the station $s \in \mathcal{S}$ to ensure the respect of the takt time.

The cost induced by the use of one machine of type i is composed of two elements: C_{Mi} the purchase cost of a machine of type i and e_i the energy spent during the life of a machine of type i multiplied by the cost of 1 kWh of electricity CF_{elec} .

Each type of machine has a convertibility score, noted v_i , which takes values between 1 and 10, for dedicated and fully flexible machines respectively. These data are inspired from (Maier-Sperdelozzi et al., 2003) where the authors take the average to calculate the measure of convertibility of machines. We use a different approach, since we do not know in advance the number of machines that we will use (it depends on the type of machine selected at each station). The machine component of the convertibility, σ'_M , is computed as the sum of the product $v_i \times N_{i,s}$ for each station s , if i is the type of machines used in this station. σ'_M is normalized to lie in $[1,10]$, using the equation (1).

$$\sigma_M = 1 + 9 \left(\frac{\sigma'_M - \sigma'_{M \min}}{\sigma'_{M \max} - \sigma'_{M \min}} \right) \quad (1)$$

$\sigma'_{M \min}$ and $\sigma'_{M \max}$ are respectively a lower and upper bound for σ'_M . They are computed by the equations (2) and (3).

$$\sigma'_{M \min} = \sum_{s=1}^{S_{\max}} \min_{i \in \mathcal{I}} (v_i N_{i,s}) \quad (2)$$

$$\sigma'_{M \max} = \sum_{s=1}^{S_{\max}} \max_{i \in \mathcal{I}} (v_i N_{i,s}) \quad (3)$$

2.2 Transport devices and convertibility

A set $\mathcal{J} = \{1, \dots, J\}$ of types of transport devices are available. Each transport type has a purchase cost of a transport C_{Tj} , and a convertibility score v_j , fixed thanks to a procedure given in (Maier-Sperdelozzi et al., 2003). The maximum number of connections that can be covered by a single device of type j is given by \bar{z}_j . For example, a classical conveyor is implemented to cover the transport between points on the straight line, while an automated guided vehicle (AGV) or an autonomous mobile robot (AMR) do not have this limitation and can cover a larger number of points. The only constraint regarding the transportation system is that the chosen transportation devices must have a total covering capacity large enough to cover all the connections of the systems.

The convertibility component related to the transportation device σ'_T is the number of transport devices of each

type multiplied by the score v_j . Similarly to σ'_M , it is normalized to lie in $[1,10]$ by equation (4).

$$\sigma_T = 1 + 9 \left(\frac{\sigma'_T - \sigma'_{T \min}}{\sigma'_{T \max} - \sigma'_{T \min}} \right) \quad (4)$$

The computation of the lower and upper bounds ($\sigma'_{T \min}$ and $\sigma'_{T \max}$) are given by equations (5) and (6), where z_{\min} and z_{\max} are lower and upper bound of the number of connections in the system (described in further details in Section 2.3).

$$\sigma'_{T \min} = \min_{j \in \mathcal{J}} (v_j z_{\min}) \quad (5)$$

$$\sigma'_{T \max} = \max_{j \in \mathcal{J}} (v_j z_{\max}) \quad (6)$$

2.3 Configuration choice and convertibility

We are inspired by Maier-Sperdelozzi et al. (2003) for a measure of configuration convertibility, but in our case the number of stations is supposed fixed and the number of machines is variable. This difference implies that the minimum increment component of the configuration convertibility is not needed in our context. Indeed, it was designed to assess the minimum amount of machines to shutoff when the product changes. In this situation, at least one machine per station must be shutdown. With a fixed number of stations, this effort does not depend on the design of the system. Thus, we do not consider it in this study. The two other components (minimum width and number of connections) are kept.

The width of the system is the fewest number of machines at the station, i.e. $\min_{s \in \mathcal{S}} N_{i,s}$ where i is the type of machines used on the station s .

The number of connections between machines is a decision of our problem. This number is bounded both by a lower and a upper bound. Indeed, since in a system each machine must be part of a production path, then it must have at least one upstream connection and one downstream connection. Moreover, it cannot be connected to more points that there are at the direct upstream and downstream level.

We can split the connections in the following parts: z_0 the number of connections upstream to the first station, $z_{S_{\max}}$ the number of connections downstream to the last station and z_s the number of connection between the stations s and $s + 1$, $s \in \llbracket 1; S_{\max} - 1 \rrbracket$.

Since there is a single point at the entrance and the exit of the system, the lower and upper bound for z_0 and $z_{S_{\max}}$ are calculated in the same manner: z_0 and $z_{S_{\max}}$ are equal to the number of machines in the first and last station, respectively.

The minimum value for z_s is the maximum between the number of machines at stations s and $s + 1$. An example with 3 stations and 9 machines is provided in Figure 1.

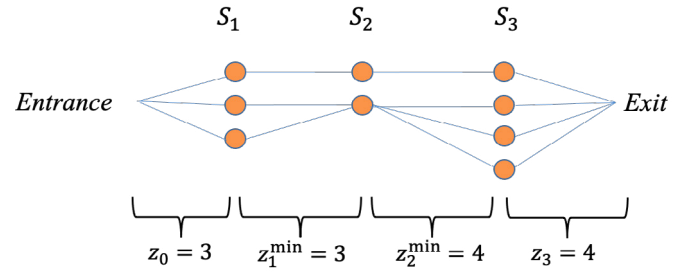


Fig. 1. Example of a system with minimum number of connections

The lower bound on the number of connections z_{\min} in the system can be computed by considering the system with the fewer numbers of machines N_s^{\min} at each station:

$$z_{\min} = N_1^{\min} + N_{S_{\max}}^{\min} + \sum_{s=1}^{S_{\max}-1} \max(N_s^{\min}, N_{s+1}^{\min}).$$

The maximum number of connections z_s^{\max} between stations s and $s + 1$ is the product of the number of machines at these stations. An example with 3 stations and 9 machines is provided in Figure 2.

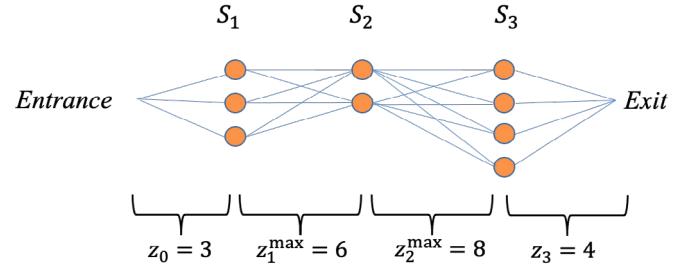


Fig. 2. Example of a system with maximum number of connections

Conversely, we can define the upper bound on the number of connections in the system, with the higher numbers of machines $N_s^{\max} = \max_{i \in \mathcal{I}} N_{i,s}$ at each station:

$$z_{\max} = N_1^{\max} + N_{S_{\max}}^{\max} + \sum_{s=1}^{S_{\max}-1} N_s^{\max} \times N_{s+1}^{\max}.$$

In this study, the configuration convertibility σ'_C is the product of the width and the number of connections of the system. Similarly to σ'_M and σ'_T , it is normalized to lie in $[1,10]$ by Equation (7).

$$\sigma_C = 1 + 9 \left(\frac{\sigma'_C - \sigma'_{C \min}}{\sigma'_{C \max} - \sigma'_{C \min}} \right) \quad (7)$$

The computation of the lower and upper bounds ($\sigma'_{C \min}$ and $\sigma'_{C \max}$) are given by equations (8) and (9).

$$\sigma'_{C \min} = \min_s N_s^{\min} z_{\min} \quad (8)$$

$$\sigma'_{C \max} = \min_s N_s^{\max} z_{\max} \quad (9)$$

3. MATHEMATICAL FORMULATION

We model the problem described in Section 2 with a mixed integer linear program with two objectives functions. The first objective function maximizes system convertibility (configuration, machine and transport convertibility) with appropriate weights for each convertibility component. The second objective function minimizes the cost of the system (purchase and operating machine cost and purchase transport cost). The summarize of parameters notations is presented in Appendix A.

The decision variables are the following:

- $x_{i,s} = \begin{cases} 1, & \text{if the type } i \text{ of machines is chosen to be used in station } s \\ 0, & \text{otherwise} \end{cases}$
- $n_{Tj} \in \mathbb{N}$: Number of transport of type j
- $y_j \in \mathbb{N}$: Number of connections of type j
- $z_s \in \mathbb{N}$: Number of connections between the stations s and $s + 1$
- $\sigma'_M, \sigma'_T, \sigma'_C \in \mathbb{N}$: Machine, transport and configuration convertibility, respectively
- $\sigma_M, \sigma_T, \sigma_C \in [1; 10]$: Normalized machine, transport and configuration convertibility, respectively

Equations (10) to (28) presents the MILP formulation of the problem.

$$\max \text{Conv}_S(i, j) = \omega_C \sigma_C + \omega_M \sigma_M + \omega_T \sigma_T \quad (10)$$

$$\min C_S(i, j) = \sum_{i=1}^I \sum_{s=1}^{S_{\max}} (C_{Mi} + \text{CF}_{\text{elec}} e_i) N_{i,s} x_{i,s} + \sum_j^J C_{Tj} n_{Tj} \quad (11)$$

$$\text{s.t. } N_{i,s} \sum_{s'=0}^{S_{\max}} z_{s'} + M_1(1 - x_{i,s}) \geq \sigma'_C \quad i \in \mathcal{I}, s \in \mathcal{S} \quad (12)$$

$$1 + 9 \left(\frac{\sigma'_C - \sigma'_{C \min}}{\sigma'_{C \max} - \sigma'_{C \min}} \right) \geq \sigma_C \quad (13)$$

$$\sum_{s=1}^{S_{\max}} \sum_{i=1}^I v_i N_{i,s} x_{i,s} \geq \sigma'_M \quad (14)$$

$$1 + 9 \left(\frac{\sigma'_M - \sigma'_{M \min}}{\sigma'_{M \max} - \sigma'_{M \min}} \right) \geq \sigma_M \quad (15)$$

$$\sum_{j=1}^J v_j y_j \geq \sigma'_T \quad (16)$$

$$1 + 9 \left(\frac{\sigma'_T - \sigma'_{T \min}}{\sigma'_{T \max} - \sigma'_{T \min}} \right) \geq \sigma_T \quad (17)$$

$$n_{Tj} \bar{z}_j \geq y_j \quad j \in \mathcal{J} \quad (18)$$

$$\sum_{j=1}^J y_j = \sum_{s=0}^{S_{\max}} z_s \quad (19)$$

$$z_0 = \sum_{i=1}^I N_{i,1} x_{i,1} \quad (20)$$

$$z_{S_{\max}} = \sum_{i=1}^I N_{i,S_{\max}} x_{i,S_{\max}} \quad (21)$$

$$z_s \leq N_{i,s} N_{i',s+1} + M_2(2 - x_{i',s+1} - x_{i,s}) \quad i \in \mathcal{I}, i' \in \mathcal{I}, s \in \llbracket 1; S_{\max} - 1 \rrbracket \quad (22)$$

$$z_s \geq \sum_{i=1}^I N_{i,s} x_{i,s} \quad s \in \llbracket 1; S_{\max} - 1 \rrbracket \quad (23)$$

$$z_s \geq \sum_{i=1}^I N_{i,s+1} x_{i,s+1} \quad s \in \llbracket 1; S_{\max} - 1 \rrbracket \quad (24)$$

$$\sum_{i=1}^I x_{i,s} = 1 \quad s \in \mathcal{S} \quad (25)$$

$$x_{i,s} \in \{0, 1\} \quad (26)$$

$$\sigma_C, \sigma_M, \sigma_T \in [1; 10] \quad (27)$$

$$n_{Tj}, y_j, z_s, \sigma'_C, \sigma'_M, \sigma'_T \in \mathbb{N} \quad (28)$$

The constraints (12)-(17) present the convertibility of the configuration, machines and transport with their normalization as described in Section 2. To note the the constraint (12) is linearized with the method of big M (Petersen et al., 1971). The constraints (18) and (19) provide the necessary number of transport to cover all connections. The constraints (20)-(21) give the number of connections at the entrance and the exit of the system. The constraint (22) is a linearization of the upper bound of connections between station s and $s + 1$: $N_{i,s} x_{i,s} N_{i',s+1} x_{i',s+1}$. The constraints (23) and (24) are a linearization of the lower bound of connections between station s and $s + 1$: $\max(N_{i,s} x_{i,s}, N_{i,s+1} x_{i,s+1})$. The constraint (25) ensures that there is only one type of machine at each station. The constraints (26) - (28) provide the definition domains of variables.

4. NUMERICAL EXPERIMENT

Now we illustrate the problem on a numerical example.

We consider three types of machines: dedicated station (type $i = 1$), standard CNC (type $i = 2$) and CNC with flexible fixtures (type $i = 3$). There are 3 stations in the system. The following matrix describes the minimum number of machines of each type at each station:

$$\begin{pmatrix} N_{1,1} = 12 & N_{1,2} = 2 & N_{1,3} = 8 \\ N_{2,1} = 5 & N_{2,2} = 2 & N_{2,3} = 3 \\ N_{3,1} = 2 & N_{3,2} = 1 & N_{3,3} = 3 \end{pmatrix}$$

To simplify the example, we do not take into account the energy consumption $\text{CF}_{\text{elec}} = 0$. We have three types of transport: conveyor (type $j = 1$), AGV (type $j = 2$) and AMR (type $j = 3$). An AGV is an autonomous vehicle traveling on rails and an AMR is an autonomous robot using camera and radar to locate itself. Thus AMR is more flexible than AGV. The data of machines and transport is given in Tables 1a and 1b, respectively.

With three types of machines and three stations, there are 27 combinations for the values of the variables $x_{i,s}$.

If there is only one admissible value for z_0 and $z_{S_{\max}}$ once the $x_{i,s}$ are set, the number of admissible values for the other z_s is large. For example, if the machines of

	v_i	C_{Mi} (mil. \$)
$i = 1$ (dedicated station)	1	1
$i = 2$ (standard CNC)	5	2
$i = 3$ (CNC with flex. fixtures)	10	4

(a) Machines

	v_j	z_j	C_{Tj} (mil. \$)
$j = 1$ (conveyor)	1	3	0.01
$j = 2$ (AGV)	5	6	0.025
$j = 3$ (AMR)	10	9	0.05

(b) Transport

Table 1. Instances of the example

type 1 are implemented on all stations, then the number of connections between the first and the second stations ranges from 12 to 24, and from 8 to 16 between the second and third stations. Thus there is up to $19 \cdot 3 = 117$ admissible combinations for the variables z_s . In addition, we have a choice between 3 types of transport. In the system, the number of connections varies from 10 to 60. The number of transport type distributions for each connection is the number of ways to write the chosen number of connections as the sum of three numbers (including 0). For z connections in the system, there are $(z + 1)(z + 2)/2$ ways. Thus, for 10 connections, there are 66 ways. For 60, the number of ways is 1891. So even in such a small example we need to use automatic process.

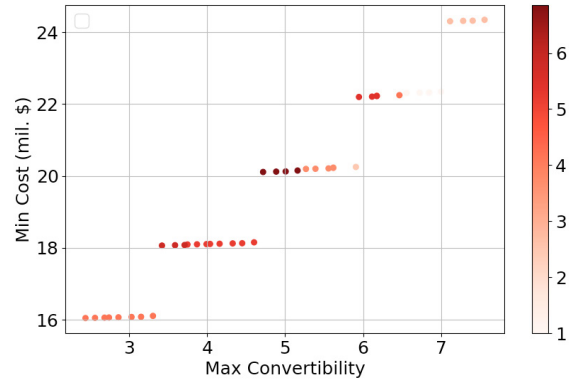
To find a solution of the example described above, the program of section 3 was implemented in Python, on a PC 13th Gen Intel(R) Core(TM) i7-13800H 2.5 GHz. The model is handled by the docplex (the IBM Decision Optimization CPLEX Modeling package for Python).

To solve the optimization problem with two objective functions, we use the ϵ -constraint method. The function of maximizing convertibility (10) is taken as the objective function, and the function of minimizing the cost (11) is taken as an additional constraint. First of all, the two lexicographic optimal solutions are computed, and starting from the one maximizing the convertibility, we gradually decrease the value of the cost, with a step of $\epsilon = 0.005$, until the other lexicographic solution is reached. The obtained solutions are filtered by dominance. Indeed, since there is no constraint imposing the number of transportation device is not higher than needed, dominated solutions can be found by the method.

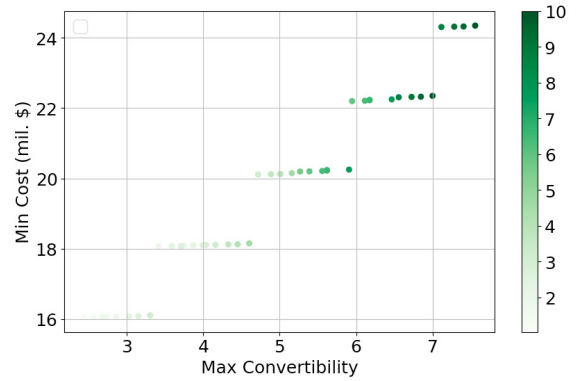
In the case of a balanced weights: $\omega_C = \omega_M = \omega_T = 1/3$, we get 43 points (processing time is 3.66 sec.). The solutions are shown in Figure 3 with the addition of the convertibility gradient for the machines and transport. The darkest points correspond to the highest convertibility.

The Pareto front has a stepped form, that is, while maintaining almost the same cost, we can increase convertibility. This behavior is explained by the selected values of the cost of the machines, with each decision using a set of machines that are more expensive, we jump to a new level.

We can observe a negative correlation of the convertibility of transport and machines. To maintain the cost in the same level, we reduce the convertibility of the machines and increase the convertibility of transport.



(a) Machine convertibility



(b) Transport convertibility

Fig. 3. Gradient of convertibility components

The Pareto front was also computed for two other sets of weights (see Figure 4). The blue dots represent a set of weights $\omega_C = 1/3, \omega_M = 7/12, \omega_T = 1/12$, there are 77 points (processing time is 3.99 sec.). The red dots represent a set of weights where the convertibility of the transport is quite insignificant and the weights of the convertibility of the machine and the configuration are equal, $\omega_C = \omega_M = 49/99, \omega_T = 1/99$, there are 130 points (processing time is 18.63 sec.).

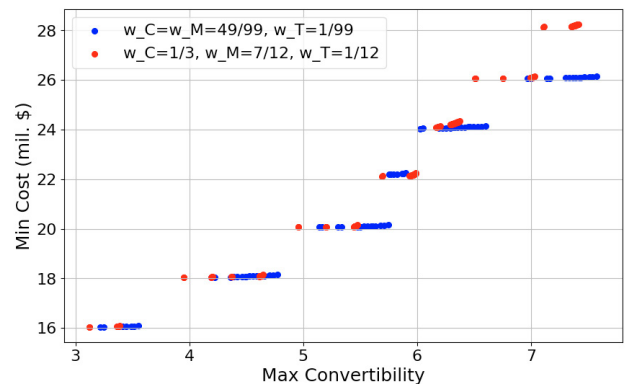


Fig. 4. Pareto front solutions for different sets of weights

On the graph, we clearly observe the grouping of values, on the same horizontal level. This is explained by the fact that in both of these sets the configuration weight exceeds the transport weight. Thus there are solutions differing only from the number of connections, forming these groups.

The comparison of optimal solutions with the maximum convertibility is presented in Table 2. We see a pattern of high convertibility of low-cost components. For instance, in the case of calibrated weights, preference is given to the convertibility of the transport and configuration, which is much lower in cost than the machines. In the second case, with the highest convertibility weight of the machine, its convertibility is maximum. Finally, the maximum cost is achieved with uniform convertibility values where the weight of transport convertibility insignificant.

	Cost	σ_C	σ_M	σ_T
$\omega_C = \omega_M = \omega_T = 1/3$	24.35	10	2.67	10
$\omega_C = 1/3, \omega_M = 7/12, \omega_T = 1/12$	26.15	4.11	10	4.5
$\omega_C = \omega_M = 49/99, \omega_T = 1/99$	28.25	7.55	7.28	7.71

Table 2. Solutions of maximum convertibility

5. CONCLUSION

We develop a deterministic mathematical framework for the contribution to the sustainable development of a RMS by increasing the system life cycle. To increase the life cycle of a RMS, we consider an indicator called convertibility, i.e., the ability of the system to adapt to market changes. Our model allows to select a type of machine per station as well as a type and quantity of transport by optimizing the convertibility and cost of a production system.

We adapted the convertibility measure proposed in (Maier-Speredelozzi et al., 2003) to formalize the decision problem of designing a RMS maximizing the convertibility and minimizing the cost. A mixed linear program is presented to formalize the problem. A numerical example illustrates the approach and shows some patterns as well the difficulty to solve this problem even for the small instances.

In the near future, numerical experiments will be conducted for a more detailed examination of the model as well as further analysis of the results. It would be interesting to consider other characteristics of the RMS that contribute to the adaptation to the market changes, as scalability. On the other hand, sustainability axes, with an environmental focus, can also open up new directions.

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Appendix A. NOTATIONS

Table A.1. Parameters notations

\mathcal{S}	Set of stations, $s = \{1, \dots, S_{\max}\}$
\mathcal{I}	Set of machine types, $i = \{1, \dots, I\}$
\mathcal{J}	Set of transport types, $j = \{1, \dots, J\}$
v_i	Ranking of the convertibility of a machine of type i
e_i	Energy spent during the life of a machine of type i
$N_{i,s}$	Number of machines of type i required at station s to ensure the respect of the takt time
C_{Mi}	Cost of a machine of type i
v_j	Ranking of transport convertibility of a transport of type j
\bar{z}_j	Number of connections that transport of type j can cover
C_{Tj}	Cost of transport of type j
CF_{elec}	Cost of 1 kWh of electricity
N_s^{\min}	Minimum number of machines at the station s , $N_s^{\min} = \min_i N_{i,s}$
N_s^{\max}	Maximum number of machines at the station s , $N_s^{\max} = \max_i N_{i,s}$
z_{\min}	Minimum number of connections, i.e. the case of the least number of machines at each station, $z_{\min} = N_{i,1}^{\min} + N_{i,S_{\max}}^{\min} + \sum_{s=1}^{S_{\max}-1} \max(N_s^{\min}, N_{s+1}^{\min})$
z_{\max}	Maximum number of connections, i.e. the case of the largest number of machines at each station, $z_{\max} = N_{i,1}^{\max} + N_{i,S_{\max}}^{\max} + \sum_{s=1}^{S_{\max}-1} N_s^{\max} N_{s+1}^{\max}$
$\sigma'_{C \min}$	Minimum configuration convertibility, $\sigma'_{C \min} = \min_s N_s^{\min} z_{\min}$
$\sigma'_{C \max}$	Maximum configuration convertibility, $\sigma'_{C \max} = \min_s N_s^{\max} z_{\max}$
$\sigma'_{M \min}$	Minimum machine convertibility, $\sigma'_{M \min} = \sum_{s=1}^{S_{\max}} \min_{i \in \mathcal{I}} (v_i N_{i,s})$
$\sigma'_{M \max}$	Maximum machine convertibility, $\sigma'_{M \max} = \sum_{s=1}^{S_{\max}} \max_{i \in \mathcal{I}} (v_i N_{i,s})$
$\sigma'_{T \min}$	Minimum transport convertibility, $\sigma'_{T \min} = \min_{j \in \mathcal{J}} (v_j z_{\min})$
$\sigma'_{T \max}$	Maximum transport convertibility, $\sigma'_{T \max} = \max_{j \in \mathcal{J}} (v_j z_{\max})$
M_1, M_2	Arbitrarily large numbers (for linearization of the mathematical program)
ω_C	Weight of configuration convertibility
ω_M	Weight of machine convertibility
ω_T	Weight of transport convertibility