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MULTI-OBJECTIVE PROCESS AND PRODUCTION PLANNING INTEGRATION IN RECONFIGURABLE MANUFACTURING ENVIRONMENT: AUGMENTED E-CONSTRAINT BASED APPROACH

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ABSTRACT: Nowadays, manufacturing systems should be cost-effective and environmentally friendly to cope with various challenges in today's competitive markets. Furthermore, being cost-effective needs to optimize the behaviour and functionality of the production system and being environmentally friendly requires to reduce the amount of harmful gasses emitted in the working area. In this context, reconfigurable manufacturing systems (RMSs) have emerged to fulfil these requirements. RMS is one of the latest manufacturing paradigms, where machines components, software or material handling units can be added, removed, modified or interchanged as needed and when imposed by the necessity to react and respond rapidly and cost-effectively to changing. In this paper, a multi-objective multi-product process and production planning problem in a sustainable reconfigurable manufacturing environment is considered. The cost function and three pillars of sustainability functions such as social, environmental, and economical are introduced and optimized. Moreover, an augmented ϵ -constraint method is proposed to solve the problem. Finally, an illustrative numerical example is presented to show the validity of the approach.

KEYWORDS: Sustainability, Process planning, Production planning, Reconfigurable manufacturing systems, Multi-Objective optimization, augmented ϵ -constraint method

1 CONTEXT AND MOTIVATIONS

In today's world, a manufacturing system has to be cost-effective and environmentally harmless to acquire sustainability and compete with other rivals in the market. According to a visionary report of Manufacturing Challenges 2020 conducted in USA, this trend will continue, and one of the six grand challenges of this visionary report is “the ability to reconfigure manufacturing systems rapidly in response to changing needs and opportunities” (Khezri *et al.*, 2019, 2020). Moreover, due to the escalation in fuel prices, higher tariff for electrical use and environmental legislations, the reduction in energy consumption and carbon footprint has become the need of the hour in the manufacturing sector.

Reconfigurable manufacturing system (RMS) is one of the latest manufacturing paradigms. In this paradigm, machine components, machines software's or material handling units can be added, removed, modified or interchanged as needed and when imposed by the necessity to react and respond rapidly and cost-effectively to changing requirements. RMS is recognized as a convenient manufacturing paradigm for variety productions as well as a flexible enabler for this variety. Hence, it is a logical evolution of the two manufacturing systems already used in the industries respectively dedicated manufacturing lines (DML) and flexible manufacturing systems (FMS). According to (Koren, 2010), DMLs are inexpensive but their capacities are not fully utilized in several situations

especially under the pressure of global competition, thus they engender losses. On the other hand, FMSs respond to product changes, but they are not designed for structural changes. Hence, in both systems, a sudden market variation cannot be countered, such as demand fluctuation or regulatory requirements. RMS combines the high flexibility of FMS with the high production rate of DML. It comprises the positive features of both systems, thanks to its adjustable structure and design focus. Thus, in situations where both productivity and system responsiveness to uncertainties or to unpredictable scenarios (e.g., machine failure, market change, ...) are of a vital importance, RMS ensures a high level of responsiveness to changes with a high performance. This can be achieved through six main principles respectively *customization, convertibility, scalability, integrability, modularity, and diagnosability*.

Moreover, (Koren, 2010) suggested that in manufacturing systems, the key to responsiveness in markets as well as cope with market changes caused by fluctuating quantities of demand, is to adjust the production system capacity. He stressed that this adjustment is possible thanks to two types of reconfiguration capabilities in manufacturing systems, which are functionality adjustment and production capacity adjustment. These characteristics are achievable because of reconfigurable machine tool (RMT), which is considered as one of the major components of RMS. Regarding reconfigurable structure designed, RMT provides a customized flexibility and offers a variety of alternatives features.

A sustainable future is the most important concern of human beings in today's world. This ability comprises of happiness, health, education, job satisfaction, and so on. It relies on most aspects of human race life such as social, environmental, and economic. Nowadays, numerous restrictions and laws are set pointing companies to lower the level of damage caused to the environment. Furthermore, they have to consider the health condition of their workers and the effects of harmful materials and remnants of the production on their bodies as well (Massimi *et al.*, 2020). RMS is able to meet these challenges due to its flexibility and integrability. Moreover, it is thought to be one of the most suitable paradigms with the requirements of sustainability.

In this paper, a multi-objective multi-unit multi-part process and production planning problem in a sustainable reconfigurable environment is addressed. Two objectives are minimized respectively the total production cost and the total harmful effects of the dangerous liquids and remnants of the production on the workers' bodies. A mathematical formulation is proposed and solved using an adapted version of the augmented ϵ -constraint method.

The rest of paper is organized as follows. Section 2 brings up some literature review. Section 3 presents the problem description and its mathematical formulation. Section 4 describes the proposed approach. Section 5 shows the applicability of the approach using a simple numerical example. Section 6 concludes the paper and suggests some future works directions.

2 LITERATURE REVIEW

As one of the newest paradigms, RMS has demonstrated great potential for further researches. In this section, we briefly review some research works in sustainability, process planning and production planning.

2.1 Sustainability in manufacturing systems

The most paramount part of sustainable manufacturing is innovative products to achieve a major part of markets share and implement a sustainable environment at the same time (Khezri *et al.*, 2019). It is necessary to shift all the production sites to sustainable product development, which is possible by using reconfigurable manufacturing systems. Besides, RMS has several advantages to impact on manufacturing process and performance as permanent changes due to answer different and situational demands of market zones. Other elements such as cost reduction, improved flexibility, and high quality of final products make RMS a suitable choice for the enabling of economic sustainability in all over the systems. Moreover, it is also plausible to implement social and environmental sustainability by the RMS (Koren *et al.*, 2018).

Considering economic sustainability, (Garbie, 2013) claimed that cost is most widely use criterion for produc-

tion environment and the consideration of the final value. In the concept of environmental sustainability, (Aljuneidi and Bulgak, 2016) believed that the implementation of the product and service design on sustainable business development can represent the system sustainability. (Dubey *et al.*, 2017) considered the role of authorities on the final RMS sustainability by the management and organizational culture as sustainable indicator. Furthermore, energy consumption that arose from the usage of the machines in the working environment can be the indicator of the sustainable environment (Choi and Xirouchakis, 2015). In the social environment, the fluctuation of the customer's demand and their satisfaction through the changes can represent the sustainability.

2.2 Process planning

One of the essential parts of RMS is process planning. Process planning leads to find the best way of manufacturing according to the shape, properties, surface, and appearance of the final product. Process planning has emerged as an important issue in the manufacturing systems because a part of the massive production can use only one process plan.

(Khezri *et al.*, 2020) developed an environmental oriented multi-objective optimization problem in an RMS. Authors considered process plan generation while introducing a sustainability metric value and counting the manufacturing cost and time to obtain optimal process plans.

2.3 Production planning

Production planning links several segments in a manufacturing environment such as operations scheduling, capacity of the output, final product quality, etc. Furthermore, quality control and process planning can play a decisive role in the decision making of the quantitative matters (Jacob *et al.*, 2019).

In this context, few research works have considered the implication of multiple production systems to produce a specific amount of the final products. (Liu *et al.*, 2019) presented a mixed integer stochastic programming model for manufacturing systems. They introduced an effective tool for optimizing the production plan rely on the decision maker point of view. (Kaltenbrunner *et al.*, 2019) considered the production planning for a highly automated pallet production. They proposed a heuristic solution approach to solve the cutting stock problem with a constraining open stack problem occurring at the beginning of the production of pallets, the saw and the downstream stacking robots. The objective is to minimize the waste of material and to ensure a continuous production flow at the pallet production site.

From the above literature review, we can conclude that the combination of process and production planning in a sustainable environment is an interesting and new topic

in the RMS. Moreover, some new approaches, like the augmented ε -constraint method, can solve the problem more precisely.

3 PROBLEM DESCRIPTION AND MATHEMATICAL FORMULATION

3.1 Problem description

In this paper, multi-unit products are considered to be produced by several reconfigurable machines. Each product requires a set of operations linked by a precedence graph (see Figure 1). The problem aims to find the optimal process plan of each product. In this section, the mathematical formulation of the problem is presented, where two objective functions are minimized:

- i) Total production cost includes the cost of operations, machines changing costs, production costs and product costs in each sequences.
- ii) Total sustainability function includes the environmental sustainability and social sustainability.

Some other assumptions are considered:

- 1- Workers just check the function of the machines during changes and process.
- 2- The machines wastes are hazardous for the human beings bodies'.
- 3- Working area is fulfilled by the hazardous gasses that can affect workers bodies'.
- 4- The demand is deterministic.
- 5- Production planning tries to consider the optimum amount of production according to the problem.
- 6- Process planning tries to find the best sequences and machines.

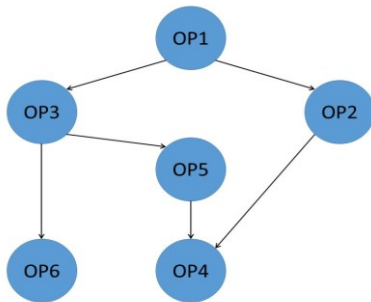


Figure 1: A simple illustrative precedence graph

3.2 Mathematical formulation

In this section, the developed multi-objective mixed-integer linear programming (MINLP) model is presented, where the following notations are used.

Sets	
i, i'	Indices of operations $\in \{1, \dots, N\}$
j, j'	Indices of position in the sequences $\in \{1, \dots, J\}$
p, p'	Indices of products $\in \{1, \dots, P\}$
m, m'	Indices of machines $\in \{1, \dots, M\}$

h, h' Indices of configurations $\in \{1, \dots, H\}$

Parameters	
N	Number of operations
M	Number of machines
J	Number of positions
BM	A big number
w_{So}	Relative weight of social issues
w_{En}	Relative weight of environmental issues
T_h	Cycle time of configuration h
CAP_h	Maximum capacity of the configuration h
$PCAP$	Production capacity
D_p	Market demand of product p in the considered period
H	Number of sequences in the considered period
TP_p	Total production time of product p
AC_{ph}	Assignment cost of product p to sequence h
$CM_{jj'm}$	Cost of changing from position j to position j' by machine number n
$TM_{jj'm}$	Time of changing from position j to position j' by machine number n
PT_{ijp}	Processing time of operation i on the product p at position j
PC_{ijp}	Processing cost of operation i on the product p at position j
PR_i	Set of predecessors of operation
QC_{ph}	Production cost of product p in configuration h
$EL_{i,j}$	Harmful liquid remnants of the operation i at position j
$EG_{i,j}$	Harmful gases emission of the operation i at position j
$l_{i,j}$	Required liquid for operation i at the position j
L	Total available liquid
EF	The effect of harmful gases on the human body during the working hours

Decision variables

x_{ijh}^p	$(x_{ijh}^p = 1)$ if operation i , of product p is processed at position j , using configuration h $(x_{ijh}^p = 0)$ otherwise
y_{jh}^{mp}	$(y_{jh}^{mp} = 1)$ if machine m , is at the position j , to produce product p using configuration h $(y_{jh}^{mp} = 0)$ otherwise
$v_{jj'}^{mp}$	$(v_{jj'}^{mp} = 1)$ if there is a change in machine m between the position j and j' , to produce product p $(v_{jj'}^{mp} = 0)$ otherwise
q^p	Production quantity of product p
AS_{ph}	Assignment matrix of the product p to sequence h
s_{So}	Sustainability indicator of the social aspect
s_{En}	Sustainability of the environmental aspect
Z_1	Cost function
Z_2	Sustainability function

Objective function (1) details the total cost, where objective function (2) presents the sustainability matters. In this research work, social and environmental aspects are considered as the sustainability matters that can have impacts other than economic factors on the human being lives during production.

$$\begin{aligned}
 \text{Min } Z_1 &= \sum_{i=1}^I \sum_{j=1}^J \sum_{p=1}^P \sum_{h=1}^H x_{ijh}^p \times PT_{ijp} \times PC_{ijp} + \\
 &+ \sum_{j=1}^J \sum_{j'=1}^J \sum_{m=1}^M \sum_{p=1}^P v_{jj'}^{mp} \times TM_{jj'm} \times CM_{jj'm} \\
 &+ \sum_{p=1}^P \sum_{h=1}^H q^p \times QC_{ph} + \sum_{p=1}^P \sum_{h=1}^H AS_{ph} \times AC_{ph} \\
 \text{Min } Z_2 &= w_{So} s_{So} + w_{En} s_{En}
 \end{aligned} \tag{1}$$

Subject to the following constraints:

$$\begin{aligned}
 \sum_{i=1}^I \sum_{p=1}^P x_{ijh}^p &= 1 & \forall j = 1 \dots J \\
 & & \forall h = 1 \dots H \\
 \sum_{j=1}^J \sum_{p=1}^P x_{ijh}^p &= 1 & \forall i = 1 \dots I \\
 & & \forall h = 1 \dots H \\
 \sum_h x_{ijh}^p \times |PR_i| & & \forall i = 1 \dots I \\
 & & \forall j = 1 \dots J \\
 & & \forall p = 1 \dots P \\
 \leq \sum_{i'} \sum_{j'} \sum_{h'} x_{i'j'h'}^p & & \forall i = 1 \dots I \\
 & & \forall j = 1 \dots J \\
 & & \forall p = 1 \dots P \\
 \sum_{h=1}^H y_{jh}^{mp} &= 1 & \forall j = 1 \dots J \\
 & & \forall m = 1 \dots M \\
 & & \forall p = 1 \dots P \\
 y_{jh}^{mp} &\geq x_{ijh}^p & \forall i = 1 \dots I \\
 & & \forall j = 1 \dots J \\
 & & \forall m = 1 \dots M \\
 & & \forall p = 1 \dots P \\
 & & \forall h = 1 \dots H \\
 \sum_i (x_{ijh}^p + x_{ij-1h}^p) &\leq v_{jj'}^{mp} + 1 & \forall j, j' = 2 \dots J \\
 & & \forall m = 1 \dots M \\
 & & \forall p = 1 \dots P \\
 & & \forall h = 1 \dots H \\
 \sum_{i=1}^I \sum_{j=1}^J x_{ijh}^p \times AS_{iph} \times H &= q^p & \forall p = 1 \dots P \\
 & & \forall h = 1 \dots H \\
 q^p &\geq D_p & \forall p = 1 \dots P \\
 q^p \times T_h &\leq CAP_h & \forall p = 1 \dots P \\
 & & \forall h = 1 \dots H \\
 AS_{ph} - AS_{ph'} + (1 & - v_{jj'}^{mp}) \times BM & \forall j, j' = 1 \dots J \\
 & - 1 \geq 0 & \forall m = 1 \dots M \\
 & & \forall p = 1 \dots P \\
 & & \forall h, h' = 1 \dots H \\
 \sum_p q^p \times TP_p &\leq PCAP & \\
 s_{En} &= \sum_{i=1}^I \sum_{j=1}^J \sum_{p=1}^P \sum_{h=1}^H x_{ijh}^p \times PT_{ijp} \times (EL_{i,j} + EG_{i,j}) \\
 \sum_{i=1}^I \sum_{j=1}^J \sum_{p=1}^P \sum_{h=1}^H x_{ijh}^p \times PT_{ijp} \times l_{i,j} &\leq L \\
 s_{So} &= \sum_{i=1}^I \sum_{j=1}^J \sum_{j'=1}^J \sum_{m=1}^M \sum_{p=1}^P v_{jj'}^{mp} \times EG_{i,j} \times EF \\
 w_{So} + w_{En} &= 1 \\
 x_{ijh}^p &\in \{0,1\} & \forall i = 1 \dots I \\
 y_{jh}^{mp} &\in \{0,1\} & \forall j = 1 \dots J \\
 v_{jj'}^{mp} &\in \{0,1\} & \forall m = 1 \dots M \\
 & & \forall p = 1 \dots P \\
 & & \forall h = 1 \dots H
 \end{aligned} \tag{2}$$

Constraint (3) ensures every operation is done according to process plan. Constraint (4) indicates that each operation is processed once for products in each configuration. Constraint (5) states that each operation is processed if all of the predecessors operations are already finished. Constraint (6) illustrates that each configuration contains machines and products. Constraint (7) ensures that if operation i performed at position p , machine m and configuration c are required. Constraint (8) shows that if there is a change in the machines between the positions or not during the production. Constraint (9) claims that the number of final products is equal to the production sides. Constraints (10) indicates that it is crucial to produce more than the customer demands in order to prevent shortage. Constraint (11) introduces the production capacities. Constraint (12) uses to break the loops in the production site of RMS. Constraint (13) indicates that the amount of production time should not exceed the available time. Constraint (14) illustrates the environmental impacts of the production. Constraint (15) considers the limitation of total required liquid in during the production process. Constraint (16) indicates the social impacts of the production. Constraint (17) is the sum of weights.

4 PROPOSED APPROACH

Several researchers categorized process plan generation as NP-hard problem (Khezri *et al.*, 2020). The proof is simple since process plan generation is aimed to assign suitable machines and configurations to each operation, it can be translated to the well-known travelling salesman problem, which is known as a NP-hard problem. By this translation, operations are taken as nodes and problem is to minimize the objectives given. For the first step, the algorithm calculates the maximum and minimum of each objective function (Mavrotas, 2009). For example, we optimize the k th objective function with consideration of all the constraints. Then, consider the set of achieved solutions for the other functions in the range of each one of them. In this case:

- $i=1$ contemplates cost objective function
- $i=2$ contemplates sustainability objective function

The using range is as follows:

$$\varepsilon_i = Fn_i^{max} - \frac{r_p}{k} \times i \text{ where } i = 2 \tag{19}$$

where i is total objective functions interval grids and ε_i is considered as the upper bound and by varying the k th objective function, the Pareto solutions can achieved. In this regard, the augmented ε -constraint method is implemented to solve the problem. Figure 2 illustrates the flowchart of the algorithm. The decision maker will choose his preference objective function and the other objective will go under the constraint of the problem. It is contemplate as the initial step.

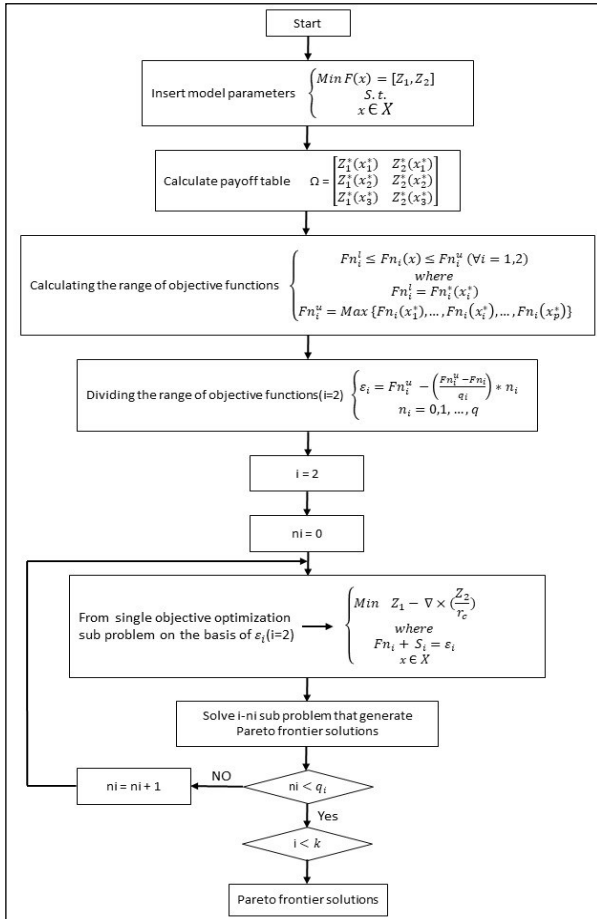


Figure 2: Flowchart of the developed augmented ϵ -constraint method

5 NUMERICAL EXPERIMENTS AND ANALYZES

In this section, an illustrative example is given and the presented mathematical formulation is implemented in GAMS 30.3.0 and test problems are solved by a laptop computer with Intel(R) Core(TM) i7-6700HQ CPU 2.60GHz and 12GB RAM.

5.1 Solving a test problem

We have three reconfigurable machines M1, M2 and M3 to produce three different products P1, P2, and P3. The sustainability effects of each one of the sustainability effectors are equal to 0.5, and three different configurations H1, H2 and H3 are available. The best generated process plans achieved by running the algorithm, and the best sequence of each product are shown in Table 1. As an example, product P3 uses machine M3 during Operation Op1 by configuration H3. The most important thing is to avoid irrational changes that increase costs. Furthermore, the pay of table of augmented ϵ -constraint method is presented in Table 2.

In this test problem, the best amount of cost function is 716.69(\$) and the amount of harmful effects of liquid and gases is 0.27 sustainability unit (S.u). The less

amount of final sustainability function shows lower environmental and social harmful impacts. Hence, we tried to minimize these values as much as possible. Moreover, for the production planning, the optimum amount of the products according to the solved problem is shown in Table 3.

Product 1	Operations	Op1 - Op2 - Op5 - Op3 - Op4 - Op6
	Machines	M1 - M1 - M1 - M2 - M2 - M3
	Configuration	H2 - H3 - H2 - H1 - H1 - H1
Product 2	Operations	Op1 - Op3 - Op2 - Op4 - Op6 - Op5
	Machines	M3 - M2 - M2 - M2 - M1 - M1
	Configuration	H3 - H1 - H1 - H2 - H2 - H2
Product 3	Operations	Op1 - Op3 - Op2 - Op4 - Op5 - Op6
	Machines	M3 - M3 - M2 - M2 - M1 - M1
	Configuration	H3 - H3 - H1 - H1 - H2 - H2

Table 1: Optimum sequence of each product

Z_1 (\$)	Z_2 (S.u)
716.69	0.60
841.22	0.27

Table 2. Payoff table of objective functions

Products	q
1	10
2	15
3	15

Table 3. Optimum product quantities

5.2 Changes of PT

Changes of the processing time, can be predictable on the sustainability function, and the increase of this parameter will increase the final answer of second objective function. But the increases of this parameter have unpredictable impacts on the cost function. Figure 3 shows the changes of this parameter.

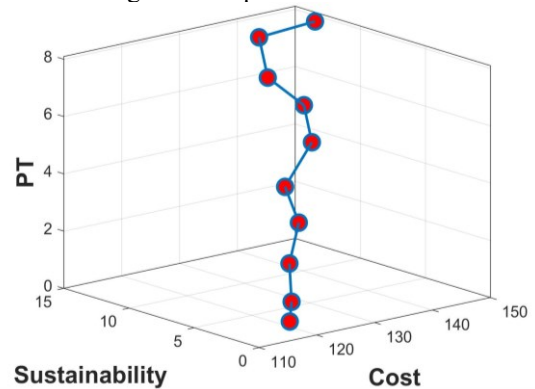


Figure 3. Changes of PT

5.3 Pareto frontier solutions

Figure 4 illustrates the Pareto frontier solutions that consist 22 different points by the running of the algorithm. As we see in the payoff table and in the chart, the best amount of cost function is 716.69(\$) when the sustainable function is 0.60 (S.u). The best amount of sustainable function is 0.27 (S.u), while the cost function is 841.22(\$). The Pareto frontier solutions obtained by

running the augmented ϵ -constraint method and it takes 157.29 seconds.

In most cases, decision makers prefer to maximize their profits; therefore, they try to minimize the cost and consider the best choice for their business. The silver lining is that by choosing the best cost, they will put their workers' health into a risky position, and it is possible to hurt them more than the usual way. Moreover, they have to obey laws that exist for human rights. In the working area, they have to consider an average point that minimum costs and doesn't cross the rolls line that means having proper sustainability objective function. On the other hand, they can't only focus on the best sustainability function. In this problem, the point with 766 (\$) and 0.37 (S.u) can be a suitable choice for a decision-maker.

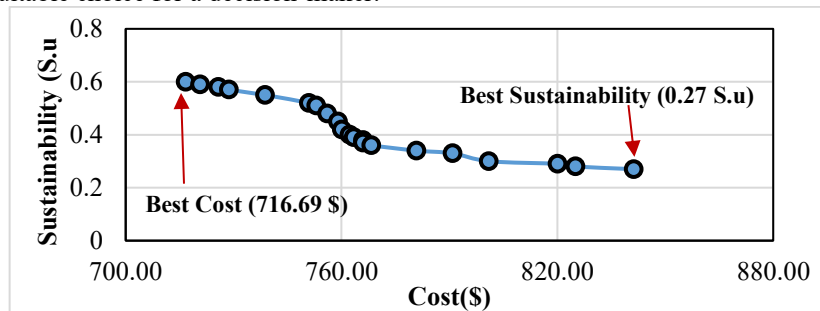


Figure 4. Pareto frontier solutions

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6 CONCLUSION

For the first time, in this paper, the process and production planning are considered in the RMS concept. Furthermore, to make the problem more realistic, all the sustainability issues, such as social, environmental, and economic are deemed. The problem has been formulated with two objective functions to minimize and solved using an adapted version of the ϵ -constraint method. For future works, new meta-heuristic algorithms or other heuristic approaches to solve the problem in a large number can be exciting. Furthermore, considering inventory management and maintenance can be useful extensions for the mathematical formulation.