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Multi-Objective Workforce and Process Planning For Socio-Economic Sustainable RMS: Lp-metric vs Epsilon Constraint

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Abstract

As a new manufacturing paradigm, reconfigurable manufacturing system (RMS) has shown promising results when dealing with market changes. This study explores the issue of integrating workforce planning and process planning within RMS. The idea is to consider socio-economic sustainable manufacturing by investigating new KPIs from the social aspect. The choice of workforce flexible work hours and the accident risk are concurrently viewed as social aspects. This challenge has been approached by using a new mixed integer linear model. Furthermore, the model considers other objectives, including operational cost and total completion time. The ϵconstraint and Lp-metric are used to solve the multi-objective model for five small and medium-sized instances. The findings demonstrate a 60% variation in reconfiguration time, and processing time contributes to 5% and 7.8% changes in makespan and 25% and 56% in total cost. Finally, some in-depth analysis is performed to illustrate and verify the performance of the suggested solution approach.

Keywords: Reconfigurable Manufacturing System, Sustainability, Workforce planning, Multi-objective optimization ;

1. Introduction

The development of the Reconfiguration Manufacturing System (RMS) seeks to create a production system that is responsive, adaptable, and flexible to changes that occur in its surrounding environment. The RMS may enhance production agility, decrease waste, and boost efficiency, ultimately leading to a more sustainable and responsible manufacturing system. This is accomplished via the use of modular equipment, flexible processes, and trained staff. Job scheduling and workforce planning guarantee that the RMS runs efficiently and uses its personnel effectively. In addition, job scheduling arranges manufacturing duties including production, maintenance, and downtime. This entails examining product demand, resource availability, and other criteria to produce an efficient, waste-free plan. This

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concept in the RMS allows the production system to quickly adapt to demand fluctuations. Workforce planning determines the number and skills of employees needed to execute the job schedule. This involves assessing the workforce's abilities and experience. In the RMS, workforce planning enables rapid staff reconfiguration in response to changes in the production system.

A Sustainable Reconfigurable Manufacturing System (SRMS) is known as a manufacturing system that is intended to be flexible and adaptive to changes in product demand and production needs. Furthermore, SRMS aims to reduce its environmental impacts and improve its social and economic advantages. The social aspect of SRMS is how the system affects the individuals involved, such as the employees, the local community, and society at large. It encompasses some key social factors including 1) workforce health and safety, 2) workforce satisfaction and participation, 3) local community impact, and 4) social responsibility and diversity, equity, and inclusion. In addition, businesses can help establish a more sustainable and responsible manufacturing system that benefits both the company and society as a whole by taking these social concerns into account when creating and implementing the RMS. This can also help to build a good brand image and attract and retain customers, investors, and potential employees.

Flexible work hours may be seen as a key performance indicator (KPI) for the social aspect. Providing flexible work hours may benefit employees by enabling them to better manage their personal and professional obligations, lowering stress levels, and increasing job satisfaction. Additionally, this may improve the general health and effectiveness of the workforce [1]. Clearly, in today's competitive employment market, flexible work hours may be a significant element in attracting and keeping personnel. Businesses that provide flexible work options may be more appealing to employees who value work-life balance and may have a higher likelihood of retaining them over the long term. Flexible work hours also reduce costs for employers as they do not need to pay overtime wages when staff can adjust their hours according to demand levels in the workplace [2].

Another social factor to consider in the design and implementation of the RMS is the likelihood of workplace accidents. The safety and well-being of the workforce should always be an important concern in any production system, as it reduces the likelihood of accidents and related injuries. Accidents in the RMS workforce can be reduced by numerous methods, including 1) safety training, 2) equipment safety, 3) workplace design, 4) hazardous materials assessment, and 5) personal protective equipment. Businesses can develop a more sustainable and responsible manufacturing system that benefits employees and society by focusing on worker safety and minimizing accidents and injuries. In general, flexible work hours and improved workforce safety may be key social aspects during the RMS and may help to create a more sustainable and responsible production system that benefits both the company and its employees.

In this research work, in addition to the total cost including operational and workforce costs and the total completion time, we consider human-centered social factors by focusing on the risk to safety of the workforce and flexible work hours. In addition, both the eligibility of the machines to carry out the operations and the qualifications of the workforce in terms of their ability to perform operations are taken into consideration concurrently. The remainder of the paper is arranged as follows. A brief review of the literature on SRMS and workforce planning is presented in the second section. The problem description and its mathematical formulation are stated in the third Section. Section four presents the adopted approaches. Section five reports the computational findings obtained. Finally, the last section concludes the paper with some future work directions.

2. Literature review

Researchers have investigated the inclusion of various aspects of sustainability in RMS. Recently, [3] presented a multi-objective mixed integer linear programming model for process and production planning in the RMS, taking into account the unemployment rate, as well as environmental and cost variables.[4] developed a multi-objective model for process planning in a reconfigurable manufacturing environment. This model took into account total production cost, time, gas emissions, and dangerous liquid wastes. [5] adopted two metaheuristics and one posterior approach for multi-objective process planning in the SRMS, where the total cost, total time, and gas emission are minimized. [6] proposed a multiobjective non-linear integer programming for process planning in SRMS. The gases imitated from the machines and hazardous liquid wastes had been considered in SRMS environmental aspects. Four adapted versions of evolutionary approaches were adopted and compared. Furthermore, the TOPSIS method was used to select the best process plans. [7] presented a mixed integer linear program for the generation of sustainable process plans in RMS where greenhouse gas emissions and total energy consumption were minimized with the makespan and total cost. The adopted versions of the simulated annealing and nondominated sorting genetic algorithm were proposed and evaluated in the multi-objective model.

In the context of workforce planning and workforce assignment, [8] provided a constraint programming-based approach to workforce planning and job sequencing in a reconfigurable manufacturing environment during the COVID-19 pandemic. [9] developed an integer programming model for job assignment and workforce planning. They focused on the scheduling of independent parallel machines and the setup duration influenced by the worker's learning curve. [10] examined an integrated employee-parallel machine scheduling issue with maximum consecutive working hours and minimum break time limits. The objective is to minimize the weighted total of makespan, machine depreciation, and workforce expenses.

Despite the focus and recent work on workforce planning and job scheduling, such as [11], [12], [13], and many more, one can notice a dearth of research on social aspects directly centered on operation/human. Most studies in the SRMS literature focus on an economic aspect and few pay attention to the issue of the unemployment rate, gas, and hazardous substance emission. According to our knowledge, the literature on SRMS suffers significantly from a lack of emphasis on the social aspect, with a particular focus on the workforce situation and their safety simultaneously.

3. Problem description

The main problem addressed in this research is the planning of the workforce and the process in SRMS. More specifically, the problem considers social factors, namely, workplace risk hazards and flexible work hours. The workforce is considered to be heterogeneous, which means that each worker has various sets of skills that allow him to work with a wide range of machines. The skill level of the workforce that uses machines is seen as a constraint. Demand refers to a part family, a group of products that share similar requirements, processes, and characteristics. Underlying assumptions of the model include:

- Workplace risk hazards include the probability of occurrence of workforce hazards and the machines' probability of an accident.
- An accident risk coefficient is assigned to each machine; this coefficient is an estimate that is derived from the history of incidents involving that equipment as well as their instructions.
- Satisfying the demand for family products is unavoidable daily, and a shortage is not allowed.
- A matrix of workforce preferences has been used to declare flexible work hours. The lower preference for starting time is more favorable.
- During each day, at most, one workforce is assigned to a machine, and vice versa.
- The processing time of an operation depends on the combination of assigned machine configuration and allocated workforce.
- At least one machine-configuration combination is capable of performing every operation. Additionally, every machine arrangement may be capable of doing many operations.
- Reconfigurable manufacturing tools are not identical, and their performance and pace can be modified by reconfiguring them. The time required to reconfigure a machine depends on current and new configurations, and the reconfiguration is performed by the worker assigned to the task.

Fig.1 shows the schematic of the investigated problem. For example, the workforce L2 is available at 9:00 a.m. based on his preference, and due to the workforce qualification for performing machines, workforce hazards, and machine accident risk, the workforce L2 will be assigned to machine M1 to perform the assigned operation to the machine. The mathematical model of the proposed multi-objective problem is presented in the following paragraphs.

Indices

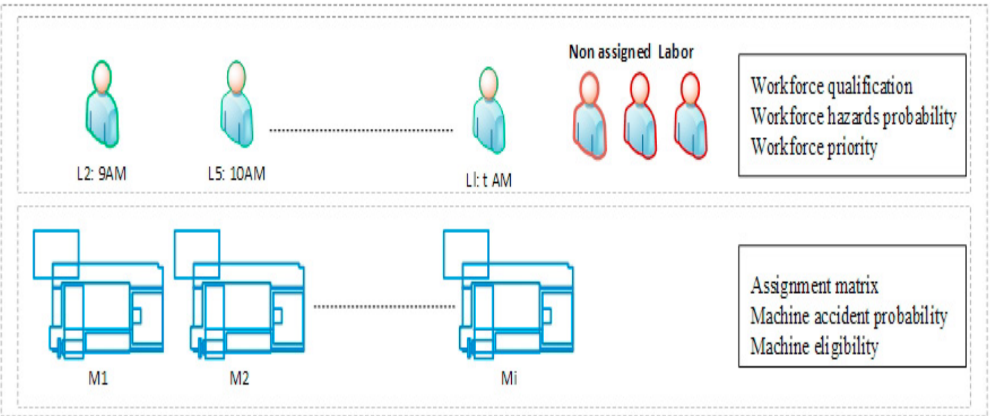


Figure 1: Problem illustration schematic.

$i \in I$	Index of operation
$m \in M$	Index of machine
$l \in L$	Index of workforce
$c, c' \in C$	Index of configuration
$t \in T$	Index of time
$p \in P$	Index of products in part family

Parameters

tp^{il}_{mc}	Time of processing of operation i perform by workforce l on machine m with configuration c
$tr^{cc'}_{m}$	Time of changing reconfiguration c to reconfiguration c' on machine m
ta_t	Starting time t
δ	Maximum legal working time
ϕ	Allowed end time per each day
i_m	Initial configuration of machine m at the start of the planning horizon
Ul_{lm}	1 if workforce l is qualified to perform on machine m based on his/her skills
UM_{imc}	1 if machine m with configuration c is eligible to perform operation i
RL_l	Workforce l susceptibility score
RM_m	Safety level risk related to machine m
mp_{pic}	Demanded operation i with configuration c for producing part family p
lP_{lt}	Workforce l priority to entry at time t
$costl_{lw}$	Per minute cost of workforce l performing with machine m
$costa_{imc}$	Cost of performing operation i in machine m with configuration c

Variables

x_{imc}	1 if operation i assigned to machine m with configuration c,and 0 otherwise
y_{lmt}	1 if workforce l assigned to machine m and starts to perform at strating time t, and 0 otherwise
$z_{ii'}$	1 if operation i scheduled before operation i' and 0 otherwise
ct_i	Completion time of operation i, and 0 otherwise
lw_{lm}	Working time of workforce l when assigned to machine m, and 0 otherwise

3.1. Objective functions

$$\text{Min} f1 = \sum_{l,m} lw_{lm} \times costl_{lw} \sum_{i,m,c} x_{imc} \times costa_{imc} \tag{1}$$

$$\text{Min} f2 = \frac{\alpha_1}{\sum_l RL_l \times \text{Max}_{\text{m}|\text{Ul}_{\text{lm}}=1} RM_m} \sum_{l,m,t} y_{lmt} \times RL_l \times RM_m + \frac{\alpha_2}{\sum_l \text{Max}_{\text{t}} lp_{lt}} \sum_{l,m,t} y_{lmt} \times lp_{lt} \tag{2}$$

$$\text{Min} f3 = \sum_i ct_i \tag{3}$$

3.2. Constraints

$$ct_i \geq \sum_t ta_t \times y_{lmt} + tr^m_{i_m,c'} + tp^{il}_{mc} - \phi \times \left[2 - x_{imc} - \sum_t y_{lmt}\right] \quad \forall i \in I, l \in L, m \in M, c' \in C \tag{4}$$

$$ct'_i \geq ct_i + tr^m_{cc'} + tp^{il}_{mc} \times -\phi \times \left[4 - x_{imc} - x_{i'mc'} - \sum_t y_{lmt} - z_{ii'}\right] \quad \forall i, i' \in I | i \neq i', l, m \in M, c, c' \in C \tag{5}$$

$$lw_{lm} \geq ct_i - \sum_t ta_t \times y_{lmt} \times -\phi \times \left[2 - x_{imc} - \sum_t y_{lmt}\right] \quad \forall i \in I, l \in L, m \in M \tag{6}$$

$$lw_{lm} \leq \delta \times \sum_t y_{lmt} \quad \forall l \in L, m \in M, t \in T \tag{7}$$

$$\sum_{m,t} y_{lmt} \leq 1 \quad \forall l \in L \tag{8}$$

$$\sum_{l,t} y_{lmt} = 1 \quad \forall m \in M \tag{9}$$

$$\sum_{m,c} x_{imc} \geq \sum_{m,c} mp_{pic} \quad \forall i \in I, p \in P \tag{10}$$

$$\sum_c x_{imc} \leq 1 \quad \forall i \in I, m \in M \tag{11}$$

$$x_{imc} \leq UM_{imc} \quad \forall i \in I, c \in C, m \in M \tag{12}$$

$$\sum_t y_{lmt} \leq Ul_{lm} \quad \forall i \in I, m \in M \tag{13}$$

$$\sum_{i,c} x_{imc} \leq |i| \sum_{l,t} y_{lmt} \quad \forall m \in M \tag{14}$$

$$z_{ii'} + z_{i'i} = 1 \quad \forall i', i \in I | i' \neq i \tag{15}$$

The first objective function (1) is concerned with cost, which includes workforce and operation assignment costs. The second objective function (2) relates to the social aspect; Workplace accident risk and workforce preference are considered, respectively. it is necessary to mention Because the terms have different values, each term is normalized by dividing it by its highest value. The objective function (3) refers to the maximum time to complete all the operations. The completion times of each operation are shown by (4) and (5). Constraint (6) refers to the calculation of the work time of each workforce. Constraint (7) identifies the maximum legal working time capacity. Constraint (8) indicates that a workforce can only work on one machine at each time, and (9) states that each machine can only be performed by one worker and also the idle machine. Constraint (10) shows operation should be performed to produce part families based on the assignment product-operation matrix. Constraint (11) states only one configuration could be chosen, and Constraints (12) and (13) state the operation assignment to machines with specific configurations and workforce assignment to machines just can happen based on the eligibility of the machine and the skill level of the operators, respectively. Constraint (14) demonstrates that the assignment of operation to machines can only occur when the workforce is dedicated to the machine. Constraint (15) displays the order of operations in the system.

4. Solution approach

Multi-objective problems may be solved using various methods, such as evolutionary algorithms, gradient-based techniques, decomposition-based methods, and hybrid methods. To solve our problem, two adopted approaches are considered: the ϵ constraint and the Lp-metric. Further explanations of the Lp-metrics and ϵ constraint are given below. As performance indicators, the total CPU time, as well as the quality of the result, are taken into consideration. The ϵ constraint provides a clear representation of the Pareto chart for the decision maker and allows them to examine the relative effectiveness of each objective function. The reformulation of the model based on the ϵ constraint approach is given as follows [14]:

$$\begin{cases} \min z_1 \\ \min z_2 \\ \min z_3 \\ s.t. \\ cons(4-15) \\ x \in S \end{cases} \rightarrow \begin{cases} \min z_1 + \varepsilon \cdot \left(\left({}^{s_2}/r_2 \right) + 10^{-1} \cdot \frac{s_3}{r_3} \right) \\ \varepsilon \in (10^{-6}, 10^{-3}) \\ z_2 + s_2 = e_2 \\ z_3 + s_3 = e_3 \\ s.t. \\ cons(4-15) \\ x \in S \end{cases}$$

Three objective functions are, correspondingly Z_1, Z_2, and Z_3 for the suggested model. Using the LP-metrics basis, the model is solved individually for the three objective functions. Z_1^*, Z_2^* and Z_3^*, respectively. A new objective function based on (16) should be considered, and the problem has to be solved based on the new objective function. Moreover, the (17) states that the sum of weights should be equal to one.

$$\text{Min} z4 = w_1 \left[\frac{z_1 - z_1^*}{z_1^*} \right] + w_2 \left[\frac{z_2 - z_2^*}{z_2^*} \right] + w_3 \left[\frac{z_3 - z_3^*}{z_3^*} \right] \tag{16}$$

$$w_1 + w_2 + w_3 = 1 \tag{17}$$

5. Computational results

In this part, the validity and performance of the model are evaluated using five randomly generated small and medium-scale cases. Additionally, the impact of crucial factors on objective values is assessed. All problems are solved on a computer with a Core i7 processor and 16GB of RAM, using GAMS software with the CPLEX solver. Each instance is denoted by I:M:L:C:P, where I, M, L, C, and P represent the number of operations, machines, workforces, configurations, and products, respectively. For instance, the I5M5L10C5P3 shows the problem set with five operations, five machines, ten workforces, five configurations, and 3 part families. The following parameters are taken from [8]: $tp_{mc}^{il} \in$ uniform$\{20, 10\}$, $ta_t \in \{480, 540, 600\}$ minutes (which correspond to 8:00 AM, 9:00 AM, 10:00 AM), and $tr_{cc'}^{m} \in$ uniform$\{10, 30\}$. The maximum allowed end time is 1080, which corresponds to 6:00 PM. The maximum working time for each worker is 480 minutes. Additionally, the following parameters are used in the generation of random numbers: $lp_{lt} \in \{1, 2, 3\}$, $costl_{lw} \in$ uniform$\{10, 15\}$ Related Money Unit (RMU), $costa_{imc} \in$ uniform$\{10, 15\}$ RMU, RM_m, and $RL_l \in$ uniform$\{0.001, 0.005\}$. Moreover, each weight of the social factor in the second objective function is equal to 0.5. The list of the parameters is summarized in Table 1.

Table 1: List of parameters.

Parameter	Value	parameter	Value
tp_{mc}^{il}	uniform {20,100}	$tr_{cc'}^{m}$	uniform {10,30}
ta_t	[480,540,600]	lp_{lt}	[1,2,3]
$costl_{lw}$	uniform {10,15 }	RM_m	uniform {0.001,0.005}
$costa_{imc}$	uniform {10,15 }	RL_l	uniform {0.001,0.005}
ϕ	1080	σ	480

Table 2: Numerical result.

	z1		z2		z3		Cpu time	
	ϵ constraint	Lpmetric	ϵ constraint	Lpmetric	ϵ constraint	Lpmetric	ϵ constraint	Lpmetric
I4M3L5C3P3	577987	369543.8	0.57	0.59	2614.6	2329.4	4.58	4.53
I5M5L10C5P3	1637744	685523.9	0.62	0.42	3550.5	3044.3	421.2	28.6
I7M6L12C5P3	1577777	2310119.9	0.64	0.66	4682	5294.15	1039	74.5
I8M6L10C5P5	2905542	2803159	0.75	0.73	6008.5	7301.5	1546	213.8
I12M8L15C5P5	3589581	3401995.6	0.76	0.73	9718	9407.5	2246	547.2

5.1. Numerical results

The findings of five medium-scale examples solved by the ϵ constraint and Lp-metric are shown in Table 2. The average values of each objective function in the payoff table for ϵ constraint are presented for each Pareto optimum solution. 10 alternative combinations of weights are taken into account in Lp-metric. Table 2 displays the mean value of the instances for several weight combinations using the LP-Metric approach. Each case has been solved for 21 grid points. Fig.2 displays the Pareto front of I5M5L10C5P3 in both approaches.

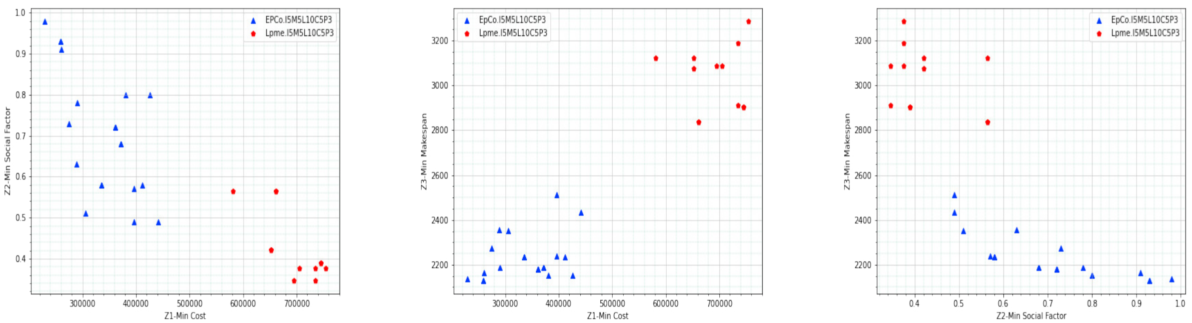
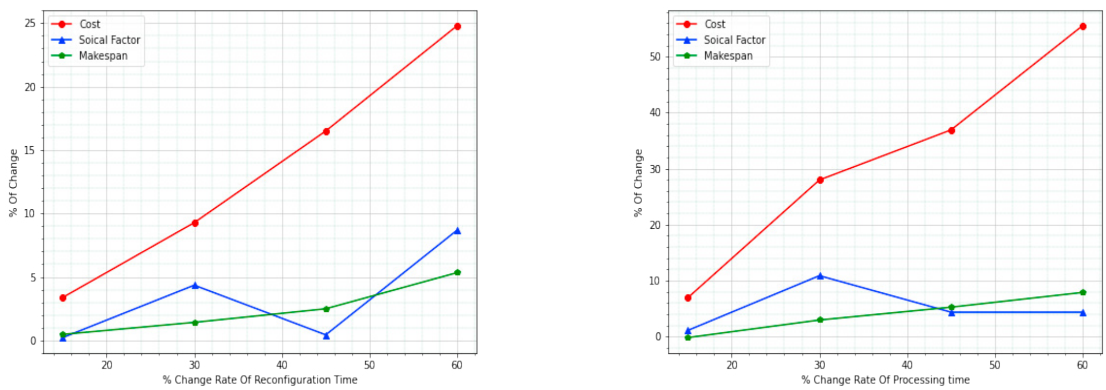


Figure 2: Pareto-optimal solution for the instances I5M5L10C5P3.

5.2. Sensitivity analysis

Changes in the values of various parameters have distinct effects on the SRMS's performances and objective functions. As a result, managers look for the most effective workforce and process planning for obtaining high performance each day. This subsection examines the influence of two essential and controllable parameters on the problem's objective functions, including 1) processing operation time and 2) configuration time. In this way, the analysis is attributed to instance I5M5L10C5P3. Four sets of random parameters are created for this issue to acquire more reliable findings, and the average changes of the four problems are presented. The following subsections declare the findings, which might give valuable insights for managers preparing for workforce assignment, production sequencing, or similar situations. Based on Fig.3a and Fig.3b, changing processing time and reconfiguration time do not have a meaningful influence on the social objective function. As a result, it is hypothesized that the change in the social objective function is just connected to the generation of random data in each set. Additionally, the change in reconfiguration time, which is analogous to chaining the processing time, has a noteworthy influence on the makespan, which is another distinctive conclusion obtained by comparing Fig.3a and Fig.3b. The makespan has undergone 7.8% and 5% changes, respectively, in the same amount of time that was spent chaining 60% of the processing and modifying the reconfiguration. Moreover, Fig.4 examines how parameters affect social factor performance. The case I5M5L10C5P3 examines how a 50% change in several parameters affects the optimal value of the social objective. The weights of the coefficient of the social factors (α_1, α_2) phrases have the most significant influence on the optimal value. The workforce priority (lP_{lt}) has the second most impact. Finally, the last two parameters, which are workforce hazard probability (RL_l) and machine accident probability (RM_m), have the most negligible influence.



(a) (b)

Figure 3: (a) impact of changing reconfiguration time, (b) Impact of processing time .

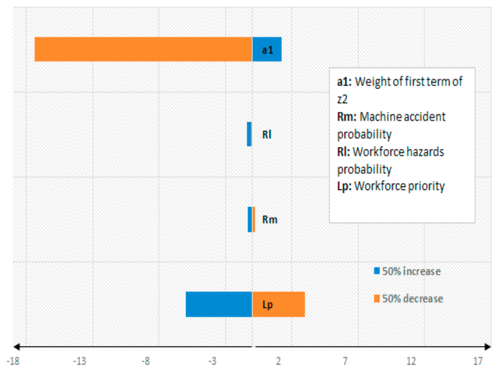


Figure 4: Sensitivity of social factor's objective function by 50% decrease and increase in related key parameter.

6. Conclusion

The purpose of this research was to offer a multi-objective approach to the sustainable process planning and workforce planning of a reconfigurable manufacturing system. The proposed multi-objective mixed integer linear model considered three objective functions to minimize, namely, operating cost, social factor, and makespan. This study's primary contribution is examining flexible work hours and the workforce's capability and machine eligibility to conduct operations. To solve the problem, the ϵ constraint and Lp-metric approaches were adapted to find Pareto-optimal solutions. The model was solved in five small and medium instances, and each objective function's result was reported. The values of the objective functions in the two approaches, as well as their solution times, were compared. Furthermore, Pareto fronts were exhibited for one instance when conducting ϵ constraint and Lp-metric approaches. In the sensitivity analysis phase, the impacts of process time and configuration change time were explored, and changes in the objective function were investigated for variations of 20, 30, 40, 50, and 60 percent of each parameter. Due to the concentration of research on new criteria of social factors in SRMS, the impacts of three related parameters, including workforce priority, workforce hazards probability, and machine accident probability, were investigated. Future research areas could include taking into account the uncertainty of the demand parameter and the processing time, as well as developing meta-heuristic algorithms for solving the model based on the type of problem. Moreover, we expect to use simulation-based optimization to illustrate better realistic scenarios adopted to SRMS.

Acknowledgement

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