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Integrated Workforce Allocation and Scheduling in a Reconfigurable Manufacturing System Considering Cloud Manufacturing

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Abstract. The reconfigurable manufacturing system (RMS) has been acknowledged as an effective manufacturing paradigm to tackle high volatility in demand types and amounts. However, the reconfiguration needs an amount of time and leads to some level of resource wastage. Accordingly, a high frequency in the system's reconfiguration may have a negative impact on its performance. In this regard, this paper investigates the advantage of using cloud manufacturing (CMfg) resources in enhancing the performance of an RMS system. A novel mathematical model is developed for the integrated workforce allocation and production scheduling problem utilizing the CMfg under a non-permutation flow shop setting. This model simultaneously makes decisions on the utilization of the CMfg capacity for performing some jobs, and for the remaining jobs, determination of machines' configurations for each job, scheduling of the jobs on the machines, and allocation of operators to machines as well. This model aims to minimize the sum of job processing costs, overtime costs, and the cost of utilizing the CMfg resources. Finally, a computational experiment is conducted, which shows a promising improvement in the total cost of the production system by utilizing the CMfg capacity.

Keywords: Scheduling, Reconfigurable manufacturing system, Workforce, Cloud manufacturing, Mathematical modeling.

1 Introduction

Over the recent decades, manufacturers have been tackling some emerging challenges, including high volatile market, mass customization, shortening of the product life cycle, globalization, and digital commerce. Accordingly, numerous attempts have been made by academia and manufacturers to survive and flourish in such situations. The reconfigurable manufacturing system (RMS) introduced in the 1990s is among the most effective and practical solutions to these challenges. Benefiting from flexible and changeable nature, in RMSs, the functionality and capacity of a manufacturing system can be

adjusted with diversity and variability of market demands in a cost-effective and timely manner [1,2].

RMSs are formed based on some key modules, which can be modified, rearranged, added, or removed to fulfill the market requirements. However, reconfigurations lead to some level of interruption in the production flow, which may result in time and resource wastage. In some cases, the manufacturing systems can even experience material wastage when test samples are needed after a reconfiguration, as well as a temporary quality decline. As a result, frequent reconfigurations in a short period diminish the advantages of RMSs in high dynamic environments [3]. For this reason, devising some strategies to cover this shortcoming of RMSs and enhance their capability is of vital importance.

Recently, thanks to new technological advancements, including cloud computing, cyber-physical system (CPS), and internet of things (IoT), a novel manufacturing paradigm, so-called cloud manufacturing (CMfg), has been introduced in the Industry 4.0 era. In CMfg systems, diverse distributed manufacturing resources can be integrated and pooled to provide services to geographically distributed customers [4,5]. Several successful implementations of this paradigm exist in the market, like Plethora, Fictive, and Xometry, to name a few. Considering the massive potential of CMfg systems in resource sharing, integrating the RMS with the CMfg concept can bring about a more productive, sustainable, and resilient system that can effectively alleviate its shortages. The nature of using the CMfg resources is similar to subcontracting or outsourcing. However, due to the advantages of the CMfg, it is now possible to find the right resources and have a price quotation within a short time [6]. As a result, these resources can be effectively incorporated into short-term planning.

Scheduling as a prominent pillar of production management has an influential role in the optimized utilization of resources. It determines the right time, resources, and workforces for the production of products respecting the performance metrics of manufacturing companies, e.g., the total costs, makespan, and total tardiness. Despite the importance of the workforce in the performance, profitability, and endurance of manufacturing companies, this factor has not been incorporated in the scheduling of RMSs so far. For this reason, this research focuses on a scheduling problem in an RMS benefiting the CMfg capacity and considering workforce requirements.

Although there is a rich literature on different areas of RMSs, scheduling problems in an RMS are in their early stages. In this regard, Ren et al. [7] studied cyclic scheduling in a flow shop problem with reconfigurable machines and developed a mixed-integer linear programming (MILP) model for it. Abbasi and Houshmand [8] sought to find the optimum sequence and size of batches and the system configuration for an RMS, in which the arrival of orders follows a Poisson distribution. Bensmaine et al. [9] provided a heuristic algorithm for joint process planning and scheduling of an RMS consisting of reconfigurable machine tools in an open shop setting. A multi-objective particle swarm optimization (MOPSO) algorithm was devised by Dou et al. [10] for an integrated configuration design and scheduling in a multi-part flow line. Ghanei and AlGeddawy [11] focused on the sustainability aspect in the joint layout and scheduling in an RMS. Mahmoodjanloo et al. [12] proposed an efficient differential evolution algorithm for a flexible job shop scheduling problem with reconfigurable machine tools.

In this paper, a scheduling problem in a reconfigurable flow shop environment consisting of a reconfigurable machine in each production stage is explored. The contributions of this paper can be summarized as follows: 1) Integrating operator allocation decisions to the production scheduling in the RMS; 2) Employing the CMfg capacity in the problem to improve the performance of the RMS; 3) Developing a novel mathematical model for the problem.

In the next section, the problem and its assumptions are first described, and then, the corresponding mathematical model is presented. Afterward, in Section 3, a computational experiment is conducted to illustrate the impact of utilizing the CMfg resources in the RMS. Finally, Section 4 concludes the paper.

2 Problem definition

In this paper, a non-permutation flow shop environment with reconfigurable machines is studied. In this case, the requested jobs visit the same order of production stages; however, their sequence on each stage may be different. Each stage consists of one reconfigurable machine with a few available configurations, which can perform a subset of jobs. In other words, there is at least one configuration eligible for processing a specific job in each stage. A machine reconfiguration may be needed to perform a job, that its required time depends on the current and new configuration. Moreover, there is a set of heterogeneous operators with different capabilities and skill levels to work on stages. As a result, the processing time of a job in a stage depends on the assigned operator and the configuration with which the job is performed.

The planning horizon is one day with a specified normal and overtime working duration. Tackling the negative impact of excessive and non-productive reconfigurations, the possibility of performing some jobs by the CMfg resources is regarded. Using the instant quoting engine of the CMfg system, the cost of performing each job is known quickly before the planning. This problem aims to determine the jobs performed by the CMfg, assign operators to stages, determine a configuration for processing each job (not performed by the CMfg) on all stages, and specify the sequence of these jobs on each stage simultaneously. The respected objective function is to minimize the total cost, which comprises job processing cost, overtime cost, and cost of utilizing the CMfg capacity. The developed MILP model and its notation are elaborated below.

Sets and Indices:

S	Set of stages
s	Index of stage
I	Set of jobs
i, i'	Indices of job
O	Set of operators
o	Index of operator
K_s	Set of configurations for stage s
k, k'	Indices of configuration, $k = b$ indicates the configuration at the beginning

Parameters:

Ω	Normal working duration
θ	Allowed overtime
Γ_i	Cost of job i in the CMfg system
Π_{sk}	Processing cost in stage s with configuration k (per unit of time)
Φ_{so}	Overtime cost rate for stage s with operator o (per unit of time)
Ψ_{so}	Capability of operator o to work on stage s (a binary parameter)
SC_{os}	Skill coefficient of operator o in stage s
P_{isk}	Normal processing time of job i in stage s with configuration k
$T_{skk'}$	Reconfiguration time on stage s from configuration k to k'
E_{isk}	Eligibility of configuration k on stage s to perform job i (a binary parameter)
L	A very large positive number

Variables:

v_{os}	1 if operator o works on stage s ; 0, otherwise.
x_{isk}	1 If job i in stage s is performed with configuration k ; 0, otherwise.
z_i	1 If job i is performed within the CMfg system; 0, otherwise.
$y_{ii's}$	1 If job i' is performed after job i in stage s ; 0, otherwise.
oc_s	Overtime cost of stage s
c_{is}	Completion time of job i in stage s
pc_{is}	Processing cost of job i in stage s

MILP model:

$$\sum_{i \in I} \sum_{s \in S} pc_{is} + \sum_{s \in S} oc_s + \sum_{i \in I} \Gamma_i z_i \quad (1)$$

s.t.

$$\sum_{o \in O} v_{os} = 1, \quad \forall s \in S \quad (2)$$

$$\sum_{s \in S} v_{os} = 1, \quad \forall o \in O \quad (3)$$

$$\sum_{k \in K_s | E_{isk}=1} x_{isk} = 1 - z_i, \quad \forall i \in I, \forall s \in S \quad (4)$$

$$y_{ii's} + y_{i'is} \leq 1 + z_i + z_{i'}, \quad \forall i, i' \in I \text{ \& } i \neq i', \forall s \in S \quad (5)$$

$$y_{ii's} + y_{i'is} \geq 1 - z_i - z_{i'}, \quad \forall i, i' \in I \text{ \& } i \neq i', \forall s \in S \quad (6)$$

$$c_{is} \geq SC_{os} P_{isk} + T_{sbk} - L(2 - x_{isk} - v_{os}), \quad (7)$$

$$\forall i \in I, \forall s \in S, \forall o \in O, \forall k \in K_s | E_{isk} = \Psi_{so} = 1$$

$$c_{is} \geq c_{is-1} + SC_{os} P_{isk} - L(2 - x_{isk} - v_{os}), \quad (8)$$

$$\forall i \in I, \forall s \in S, \forall o \in O, \forall k \in K_s | E_{isk} = \Psi_{so} = 1 \& s \neq 1$$

$$c_{i's} \geq c_{is} + SC_{os}P_{i'sk'} + T_{skk'} - L(4 - x_{isk} - x_{i'sk'} - v_{os} - y_{ii's}), \quad (9)$$

$$\forall i, i' \in I, \forall s \in S, \forall o \in O, \forall k, k' \in K_s | E_{isk} = E_{i'sk'} = \Psi_{so} = 1 \& i \neq i'$$

$$c_{is} \leq \Omega + \Theta, \quad \forall i \in I, \forall s \in S \quad (10)$$

$$oc_s \geq \Phi_{so}(c_{is} - \Omega) - L(1 - v_{os}), \quad \forall i \in I, \forall s \in S, \forall o \in O | \Psi_{so} = 1 \quad (11)$$

$$pc_{is} \geq SC_{os}P_{isk}\Pi_{sk} - L(2 - x_{isk} - v_{os}), \quad (12)$$

$$\forall i \in I, \forall s \in S, \forall o \in O, \forall k \in K_s | E_{isk} = \Psi_{so} = 1$$

$$v_{os}, x_{isk}, z_i, y_{ii's} \in \{0,1\}, \quad oc_s, c_{is}, pc_{is} \in \mathbb{R}^+ \quad (13)$$

The objective function (1) is the sum of the cost of processing jobs inside the factory, overtime cost, and the cost of allocating jobs to the CMfg resources. Constraints (2) and (3) ensures that one operator is allocated to a stage, and an operator only works on one stage, respectively. Constraint (4) determines the configuration of a job in a stage if the job is processed in the factory. Constraints (5) and (6) specify the sequence of jobs in stages if processed in the factory. Constraints (7) – (9) calculate the completion time of the jobs inside the factory for each stage based on the respected configurations, assigned workers, and sequence of jobs. Constraint (10) limits the working duration. Overtime cost in each stage is specified in Constraint (11). The processing cost of each job in each station is calculated by Constraint (12). Finally, Constraint (13) defines the domains of the variables.

3 Computational experiments

In this section, an instance with eight jobs, four operators, four stages, and three configurations for each machine in all stages is considered. The operators capable of working on each stage, the possible configuration for performing the jobs in the different stages, and the initial configuration of each stage are presented in Table 1. The other parameters, described in Table 2, are randomly generated. It should be noted that to set overtime cost rate (Φ_{so}), 20% of the average processing cost rate (i.e., 70\$) as the additional overhead cost during the overtime, plus 50% of the average hourly wage of a worker (i.e., 20\$) concerning his/her skill level, as the additional wage, are accounted. Moreover, since the prices in the CMfg are very competitive, the minimum and maximum possible cost of a job, processed inside the system, plus 10% transportation cost, is regraded for the cost range of the job in the CMfg. The proposed model is solved by the CPLEX solver in GAMS 24.1 on a PC with Processor Intel (R) Core (TM) i5-7300HQ 2.5GHz and 12 GB of RAM.

Table 1. Capable operators for stages and the required configuration for each job per station

Stage	Operators	Jobs {Configurations}								Configuration at the beginning
		i1	i2	i3	i4	i5	i6	i7	i8	
s1	{o1/o2}	{k1}	{k2}	{k1}	{k2}	{k2}	{k1}	{k3}	{k2}	k2
s2	{o2/o3}	{k4/k5}	{k5}	{k5}	{k5}	{k5}	{k6}	{k4}	{k5}	k5
s3	{o1/o3}	{k9}	{k8}	{k8}	{k7}	{k9}	{k8}	{k7}	{k8}	k8
s4	{o1/o4}	{k12}	{k11/k12}	{k11}	{k10}	{k11}	{k11}	{k10}	{k12}	k12

Table 2. Other parameters of the instance

Parameters	Unit
$P_{isk} = U[0.5, 1]$	Hour
$T_{skk'} = U[0.75, 1.5]$	Hour
$\Omega = 8$	Hour
$\theta = 4$	Hour
$\Pi_{sk} = U[40, 100]$	\$
$SC_{os} = U[0.9, 1.1]$	---
$\Phi_{so} = 0.2 * 70 + \frac{0.5 * 20}{average_{s' \in S \Psi_{os'}=1}(SC_{os'})}$	\$
$\Gamma_i = 1.1 * U \left[\sum_{s \in S} \min_{k \in K_s, \theta \in O E_{isk}=\Psi_{os}=1} SC_{os} P_{isk} \Pi_{sk}, \sum_{s \in S} \max_{k \in K_s, \theta \in O E_{isk}=\Psi_{os}=1} SC_{os} P_{isk} \Pi_{sk} \right]$	\$

The instance is solved under two strategies: 1) without considering the CMfg capacity and 2) by considering the CMfg capacity, and the corresponding Gantt charts are depicted in Figs. 1 and 2, respectively. In these charts, the stages and their allocated operators are shown on the vertical axis. For example, s1-o2 indicates operator 2 was allocated to stage 1. Also, each job is represented by a unique color and number. Re-configurations are also characterized by k*-k* format. For instance, in Fig. 1, the first reconfiguration on stage 1 is from configuration k2 to configuration k1 (k2-k1). Accordingly, all jobs before this reconfiguration are performed by configuration k2, and the following jobs before the subsequent reconfiguration are processed by configuration k1. As it is clear, utilizing the CMfg capacity considerably improves both the total cost (8.9%) and the makespan (24.6%).

To assess the impact of jobs' costs in the CMfg on the justification of utilizing the CMfg, a sensitivity analysis is conducted and shown in Fig. 3. In this figure, the percentage of jobs processed by the CMfg, and the percentage of changes in the total cost by changing the jobs' costs in the CMfg (concerning the values of Γ_i provided in Table 2) are depicted in a combined graph. For instance, when the costs of the jobs in the CMfg are increased 15%, 25% of jobs are performed by the CMfg, and the total cost is increased by 4.4%. Based on the result, even by increasing this cost up to 40%, one job is performed by the CMfg, and even in this case, using this strategy is effective and viable (i.e., the total cost is still lower than the case without using the CMfg). Finally, by increasing this cost to 45%, no job is sent to the CMfg.

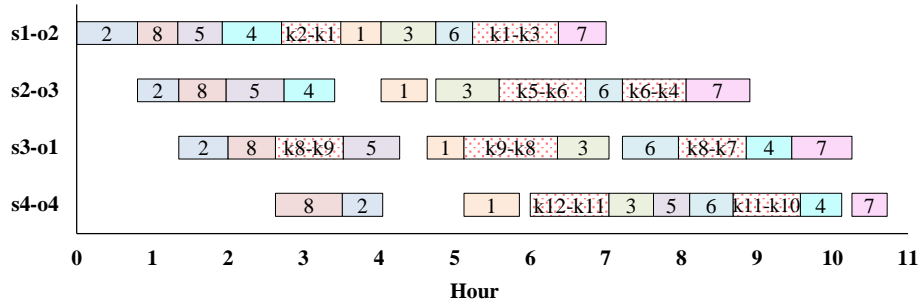


Fig. 1. Gantt chart of the instance without considering the CMfg capacity, objective=1342.49\$

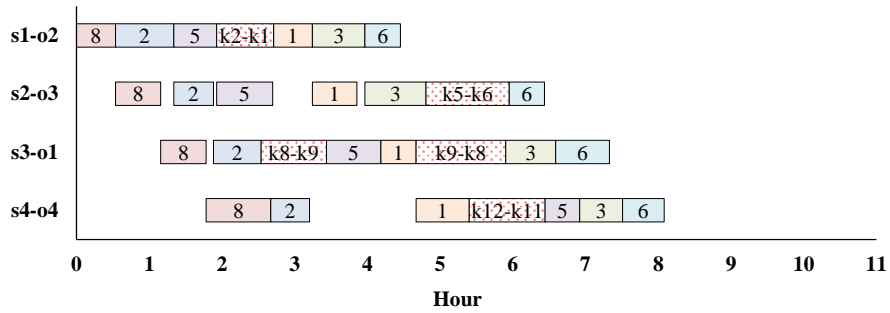


Fig. 2. Gantt chart of the instance considering the CMfg resources, objective=1232.27\$

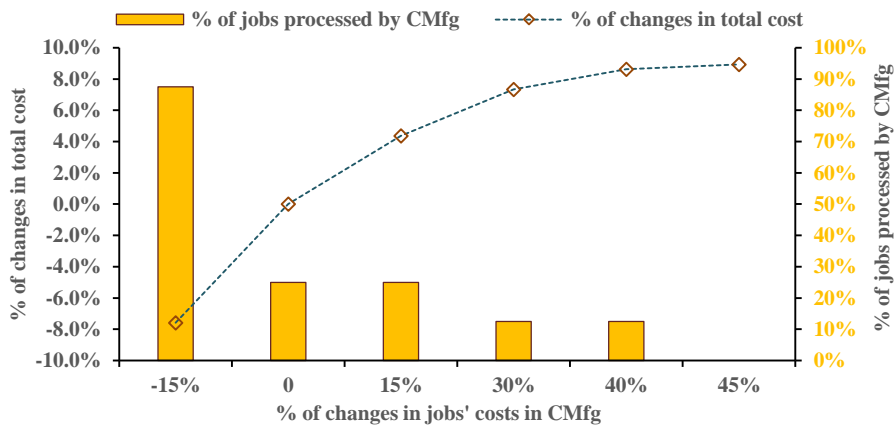


Fig. 3. Impact of jobs' costs in the CMfg on the total cost and percentage of jobs processed by CMfg

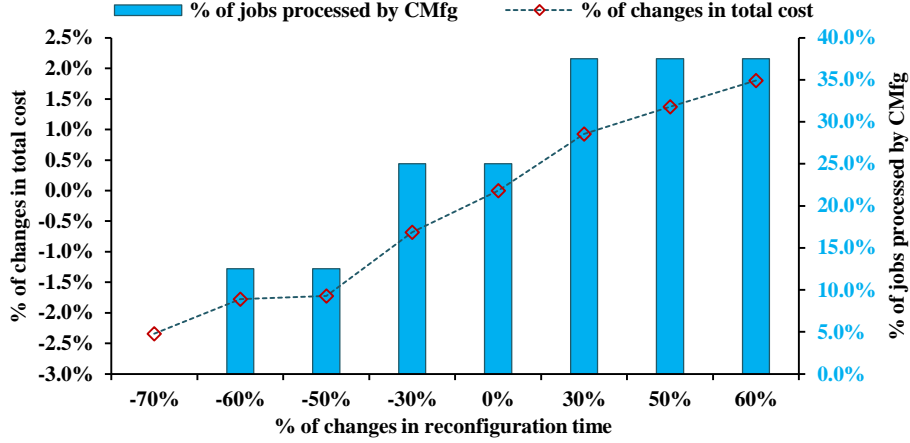


Fig. 4. Impact of reconfiguration time on the total cost and percentage of jobs processed by the CMfg

Moreover, the impact of the reconfiguration time on the total cost and the percentage of jobs processed by the CMfg is depicted in Fig. 4. Accordingly, despite a 60% decline in the reconfiguration times (concerning the values of $T_{skk'}$ reported in Table 2), the utilization of the CMfg resources is still viable. Furthermore, due to the possibility of using the CMfg, a 60% increase in the reconfiguration times only leads to a roughly 2% rise in the total cost. It means that incorporating the CMfg resources in RMSs can considerably enhance its performance.

4 Conclusion

This paper dealt with an integrated workforce allocation and production scheduling problem in a reconfigurable flow shop environment. To improve the proposed system regarding excessive and non-productive reconfiguration, utilizing the cloud manufacturing (CMfg) capacity was proposed. A novel mixed-integer linear programming (MILP) model was developed for the problem to simultaneously make decisions on using the CMfg capacity, operator allocation, machine reconfiguration, and job scheduling. Afterward, an instance was considered to assess the viability of the proposed strategy. Based on the result, utilizing the CMfg resources can considerably reduce the total cost and makespan of the system.

To extend this research, we will investigate a multi-day horizon with night disruptions and transport times to the CMfg, and provide an efficient solution approach, especially for solving medium- and large-sized problems. Incorporating the uncertainty of the parameters (e.g., processing times) and exploring the dynamism of the production system (e.g., dynamic arrival of jobs) can also be considered for future research in this topic.

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