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PLANNING AND SCHEDULING IN RECONFIGURABLE MANUFACTURING SYSTEMS FOR MASS CUSTOMIZED PRODUCTS

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Abstract: *Nowadays, industries are gradually shifting to offer mass customized products for their customers. However, mass customization requires flexible manufacturing systems. Hence several researchers are dedicated to optimize the design and the control of flexible manufacturing systems, of which reconfigurable manufacturing systems. Mass customization increases the complexity of production planning. This complexity also increases for flexible and reconfigurable manufacturing systems. This paper focuses on the complexity of planning and scheduling in reconfigurable manufacturing systems for mass customized products. It presents a simplified linear model to minimize the tardiness and its related penalty in scheduling by considering the reconfiguration time. Numerical experiments in CPLEX validate the model.*

Key Words: ***Reconfigurable manufacturing system, Mass customization, Planning, Scheduling***

1. INTRODUCTION

The environment of market has changed a lot due to the development of productivity. Sufficient global supply allows customers to demand highly diverse products, but they don't want to spend much more for acquiring this diversity. This situation challenges most companies and requires them to rethink their organization to guarantee both product diversity and slight fluctuation in cost. The modern concept 'Mass Customization' (MC) might be an effective way to help manufacturers survive in today's violent market competition. It is devoted to produce a certain degree of customized products within a cost that is close to mass production. However, mass customization requires flexible manufacturing systems[1]. Dedicated Manufacturing Line (DML) is not suited for mass customization. The Next Generation Manufacturing Systems (NGMSs) like Flexible Manufacturing system (FMS) still have too many difficulties to be widely applied in the real commercial conditions[2].

Reconfigurable Manufacturing System (RMS) may be an appropriate solution to facilitate the transformation from mass production to mass customization. It combines the advantages of high-efficiency in DML and the flexibility in FMS[3]. RMS can process a set of operations for jobs in the same part family[4]. Every part family has plenty of part variants with the similar structures and functions. These part variants differ in attributes since their producing parameters and operation sequences are various. RMS can produce a huge amount of jobs in batches to prevent obvious increasing of cost[5]. Meanwhile, these jobs belonging to different part variants will compose to different products according to each customer's distinctive demand. Hence RMS is huigly suited for mass customization.

All part variants in the same part family can be processed in a certain reconfigurable manufacturing system. A reconfigurable manufacturing system consists of multiple machines that can perform abundant operations. In other words, each machine can perform more than one operation. For each job processed in RMS, reconfiguration may occur in machine level or system level[6]. If the reconfiguration is at machine level, this means all machines can change their configuration to process different operations. Whereas on system level, this means we can add/remove or change the position of machines in the layout to create new manufacturing systems

Separate research on reconfigurable manufacturing system or mass customization has already started since the last century. But the research concentrating on how to achieve mass customization in RMS is still limited. Thanks to technological development RMS can be implemented, for example the plug-and-produce device can enable fast reconfiguration in the hardware[7]. However, facing the incremental increase in degree of complexity for production management, the issue on how to plan, control and organize the reconfigurable manufacturing system becomes critical. Planning and scheduling are already relatively complex tasks for DML and mass production. MC and RMS each increase the complexity of these tasks due to high demand variability, and increased possible configurations for the product and the process. Hence, the question of planning and scheduling in RMS for mass customized products deserves more studies in depth.

This paper proposes a first approach to answer this question. The paper is organized as follows: Section 2 presents related works; Section 3 proposes a simple mathematical model and its numerical experiment in CPLEX; Section 4 concludes the contributions and limits of this work.

2. LITERATURE REVIEW

2.1. Methodology

A literature review was conducted in different databases, including Elsevier (sciencedirect.com), Springer (springerlink.com), IEEE (ieeexplore.ieee.org), and Taylor & Francis (tandfonline.com). Figure 1 presents the literature review flowchart. We first used the keywords ‘reconfigurable manufacturing system’ and ‘mass customization’ to search the related papers in the above four databases. Then we browsed all the titles of the searching results. For papers containing words like 'reconfigurable', 'customized', 'modular' or its derivatives in the title , we continued to read the abstract. If the abstract shows that this paper is related to the searching topic, the full paper will be downloaded. Hereafter, we separately used the keywords ‘planning’ , ‘scheduling’ and ‘layout’ with ‘reconfigurable manufacturing system’to find the relevant articles of these three topics.

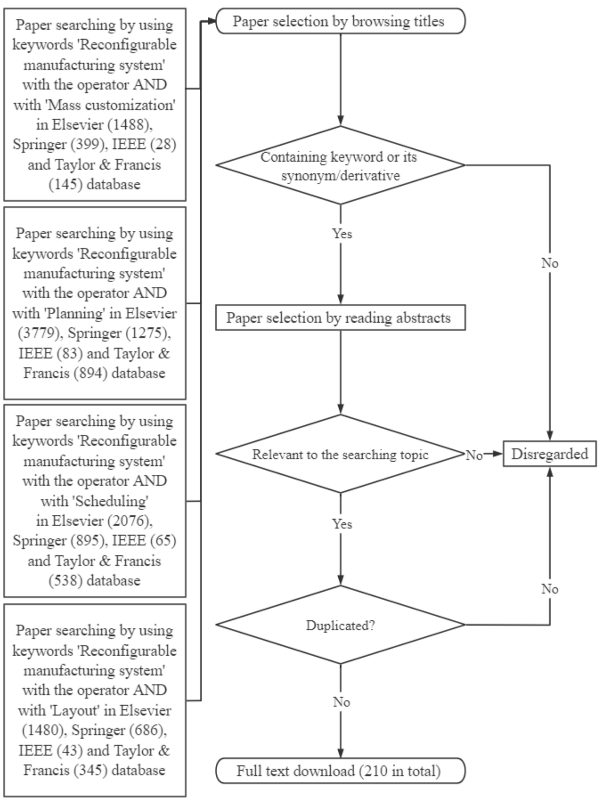

Fig. 1. *Literature review flowchart*

As shown in Figure 2, the selected articles include 210 papers, while 49 papers focus on mass customization in RMS (23%), 77 papers focus on planning in RMS (37%), 54 papers focus on scheduling in RMS (26%) and 30 papers focus on layout in RMS (14%).

Figure 3 shows that the research interest on production management in RMS for mass customized products has grown from 2000 (Incomplete data in 2020). Research on mass customization in RMS increased significaty in the first ten years, compared to the other three topics. Articles in this period mainly discuss the concepts of the related techniques or service that can be applied for mass customization in RMS. Then some works give the architecture to better perform mass customization in RMS. Research on planning and scheduling for mass customized products in RMS has increased sharply since 2010. By building mathematical models, researchers can optimize the production process of parts and components to improve the usage of resources, including facilities, capital and labors. In addition, meta-heuristic algorithms are the most popular methods used to solve this kind of optimization problem. Research on the layout problems for mass customized products in RMS has just started in the recent five years. It often considers the dynamic relationship between machines and workstations or the routing of Automatic Guided Vehicle (AGV).

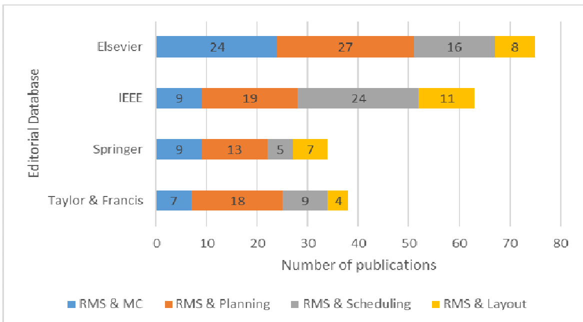

Fig. 2. *Number of publications in different Editorial Database*

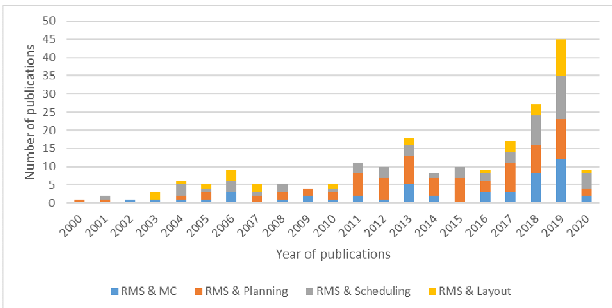

Fig. 3. *Number of publications in different years*

2.2. Research on RMS and on RMS for mass customization

Different researchers proposed disparate production frameworks of RMS from various aspects. [8] proposed a framework for a stochastic model of an RMS, which involves the optimal configurations in the design, the optimal selection policy in the utilization, and the performance measure in the improvement. [9] presented a communication framework between the coordinator, workstation agents, and executors to facilitate the reconfiguration process of manufacturing systems.

Hence, the architecture of the reconfigurable manufacturing system for mass customization has not formed a consistent understanding. Research on mass customization in RMS typically has three research directions, including framework and architecture development, configuration design, and products grouping and selecting. [10] proposed a framework for the design of a reconfigurable and mobile manufacturing system. [11] defined the core characteristics and design principles of reconfigurable manufacturing systems and describes the structure recommended for practical RMS with RMS core characteristics. [12] proposed a tree-based method to determine the configuration design for reconfiguration of a reconfigurable machine tool (RMT). [13] formulated a mixed integer linear programming (MILP) model to design the configuration of scalable RMS. [14] outlined a multi-objective approach to optimize the RMS design by modularity assessment. [15] built an integer nonlinear mathematical model (MINLP) to optimal selection of module instances for modular products. [16] used the Analytical Hierarchical Process (AHP) to group products into families. Other topics may involve the sustainability of RMS design and new technology. [17] developed a heuristic-based integer mixed non-linear approach for optimizing modularity and integrability in a sustainable reconfigurable manufacturing environment. [18] evaluated the performance of RMSs with different convertibility levels by using sustainable manufacturing metrics. [19] proposed a novel digital twin-driven approach for rapid reconfiguration of automated manufacturing systems.

2.3. Planning for mass customized products in RMS

Research on planning for mass customized products in RMS involves two confusing concepts, process planning and production planning. Process planning is the act of preparing detailed operating instructions for turning an engineering design into an end product[20]. Production planning is usually regarded as a more abundant concept including the manufacturing system modeling, configuration generation and selection, process planning, capacity planning and machine scheduling[21]. Earlier research for mass customized products in RMS generally just focused on process planning. However, the recent research starts to concentrate more on production planning in RMS, which will involve both the planning and scheduling problems. [22] built a a multi- objective model with the aim of reducing the manufacturing cost and time in process planning. [23] applied a meta-heuristic and the non-dominated sorting algorithm (NSGA-II) to a multi-objective process planning problem considering the makespan, machining cost and machine utilization. [24] developed an optimization algorithm based on Genetic Algorithm to determine the most economical way of accomplishing the system reconfiguration by adding or removing machines to match the new throughput requirements and concurrently rebalancing the system for each configuration. [25] adapted non-dominated sorting genetic algorithm (NSGA-II) to get the optimal machines sequence in RMS. [26] developed a solution algorithm based on a meta-heuristic method to solve the process planning problem based on discrete Particle swarm optimization (DPSO). [27] formulated a dynamic programming to propose a feedback adaptive strategy which provides a better control of the reconfiguration sequence and the production rate of the system and minimizes a cost function. [28] adopted Archived Multi Objective Simulated Annealing (AMOSA) to generate the process plan in RMS by considering the total completion time and machines balancing. [29] proposed a simulation based Non dominated Sorting Genetic Algorithm (NSGA-II) approach to solve the problem of process plans generation for multi-unit single-product type observed in RMS. [30] proposed a production line planning method based on reconfigurable cells with the idea of modularization design.

The above researches mainly focus on the objectives of time and cost for planning optimization. For time optimization, parameters like due date, set-up time and operation time are taken into consideration. For cost optimization, material cost, handling cost and the operation cost will often be considered. Sustainability and uncertainty are gradually taken into consideration in the recent research works. [31] developed a production planning model with the multi-objective function for minimizing the energy consumption and maximizing the throughput in a RMS. [32] surveyed different methodologies including stochastic mathematical programming, fuzzy mathematical programming, simulation, metaheuristics and evidential reasoning to deal with aggregate production planning in presence of uncertainty.

2.4. Scheduling for mass customized products in RMS

Research on scheduling for mass customized products in RMS mostly adopt the job shop theory while considering facilities flexibility in machine level or in system level in the mathematical model.

Flexibility in machine level can be met by changing reconfigurable manufacturing tools or the configuration. [33] dealt with a flexible job shop scheduling problem with RMTs by formulating two mixed-integer linear programming models with the position-based and sequence-based decision variables to minimize the maximum completion time. [34] integrated optimization problem of configuration design and scheduling for RMS by presenting a multi-objective particle swarm optimization (MoPSO) based on crowding distance and external Pareto solution archive.

Flexibility in system level can be satisfied by adding, removing and repositioning production machines or cells in a RMS. [35] presented a mathematical approach for distributing the stochastic demands and exchanging machines or modules among lines (which are groups of machines) for adaptively configuring these lines and machines for the resulting shared demand under a limited inventory of configurable components. [36] presented a genetic algorithm used for dynamic product routing in RMS.

One paper [37] considered flexibility in two levels by developing two novel effective position-based and sequence-based mixed integer linear programming

(MILP) models for solving both partially and totally flexible job shop scheduling problem.

Most papers did not indicate the level of flexibility while they just considered the cost and time of reconfiguration as given parameters. [38] formulated a mixed-integer linear programming model considering both family sequencing and operations sequencing inside each family. [39] developed a mixed integer nonlinear programming model to determine optimum sequence of production tasks, corresponding configurations, and batch sizes. [40] minimized the make span of the product by segregating and scheduling the similar operations of product in RMS. [41] introduced an two-objectives optimization model to achieve the robust scheduling by a genetic algorithm (GA) embedded with extended timed-place petri nets (ETPN). [42] proposed a genetic algorithm (GA) with parallel chromosome coding scheme to solve the integrated modular product scheduling and manufacturing cell configuration problem in RMSs.

2.5. RMS layout configuration for mass customized products

Research on RMS layout configuration for MC is the latest topic among the three research questions. The dynamic changes in real time challenge the robustness of the manufacturing system.

Some papers considered the layout problem for mass customized products in RMS by dispatching the resources to the given locations. For example, [43] considered a two-objectives model to allocate a number of identical mobile robots to the workstations. [44] proposed two-phase-based approach combines the well-known metaheuristic, archived multi-objective simulated annealing (AMOSA), with an exhaustive search–based heuristic to determine the best machine layout for all the selected machines of the product family. [45] adopted a negotiation model for solving the problem of allocating production plants to product groups without specific location information.

Other papers considered this problem by arranging a rectangle/circle machines or other kinds of equipment (like robots and manufacturing cells) in a given two-dimensional workshop. [46] proposed a chaotic generic algorithm with improved Tent mapping to solve the problems associated with the organization of the dynamic facility layout in RMS. [47] established a mathematical model of the equipment layout in the RMS workshop and designed the fitness function with penalty factor which is based on the minimum principle of logistics cost and the physical constraints of the workshop layout. [48] proposed a layout optimization method for manufacturing cells and an allocation optimization method for transportation robots in RMSs was solved by using a particle swarm optimization method.

Table 1. *Summary of Recent Publications Related To RMS planning, scheduling and layout optimization problems*

year	Ref.	Objective Functions			Problems			Approaches	
		Cost	Time	Others	Planning	Scheduling	Layout	Models	Resolving Method
2020	[33]		√			√		MILP	DE
2020	[34]	√			√	√		MILP	PSO
2019	[35]	√				√		MILP	Simulation
2019	[43]	√	√		√		√	MINLP	SA
2019	[44]			√			√	MINLP	AMOSA
2019	[46]	√		Utilization of workshop area			√	MONLP	GA
2019	[47]	√					√	LP	PSO
2018	[2]	√	√	GHG	√			MOILP	AMOSA
2018	[36]			Energy cost	√	√		NLP	GA
2017	[25]		√	Failure correctness	√			MONLP	NSGA-II
2017	[26]		√		√			ILP	DPSO
2017	[40]		√	Machine loading balance		√		MINLP	Evaluation
2015	[31]			energy consumption	√			MOLP	CPLEX
2015	[38]		√			√		MILP	Simulation
2014	[23]	√	√	System utilisation	√	√		MONLP	NSGA-II
2014	[27]	√			√			MONLP	Dynamic Programming
2013	[28]	√			√			MONLP	AMOSA
2013	[37]		√			√		MILP	AISA
2011	[29]	√	√		√			MONLP	NSGA-□
2010	[39]	√				√		MINLP	GA
2009	[30]		√		√			NLP	GA
2006	[41]	√		Balanced production		√		MONLP	Petri Nets & GA
2006	[48]		√	Distance			√	NLP	PSO
2005	[5]		√				√	MILP	Discrete Dynamic Programming

2005	[42]	√				√		ILP	GA
2005	[45]	√					√	MIP	Simulation

GHG: Greenhouse Gases; LP: Linear Programming; ILP: Integer Linear Programming; MIP: Mixed Integer Programming; NLP: Non-Linear Programming; MILP: Mixed Integer Linear Programming; MINLP: Mixed Integer Non-Linear Programming; MOILP: Multi-Objective Integer Linear Programming; MONLP: Multi-Objective Non-Linear Programming; DE: Differential Evolution Algorithm; GA: Genetic Algorithm; SA: Simulated Annealing; PSO: Particle Swarm Optimization; AISA: Artificial Immune and Simulated Annealing; NSGA: Non-dominated Sorting Genetic Algorithm; AMOSA: Archived Multi-Objective Simulated Annealing

2.6. literature review summary and Conclusion

Table 1 presents the summary of the recent works dedicated to optimizing planning, scheduling and layout configuration for RMS and in the context of MC. It summarizes the mathematical models used (objective functions, decision variables) and solution methods for the recent publications related to RMS planning, scheduling and layout optimization problems.

From this table, we can find that until this moment, most research on production management in RMS for mass customized products just concentrated on sovling one problem, and the planning problem is the most concerned issue. Three researches ([23], [34], [36]) in our survey started to focus on planning and scheduling problems at the same time, while only one article [43] proposed to integrate the planning and layout problem. For solution methods, one third of the papers have multi-objectives. And half of the mathematical models adopted integer variables. Since more than half of the models are non-linear, the meta-heuristic algorithms are widely used to solve these problems, among which the genetic algorithm is the most popular methods as more than 33% papers in our survey used it.

Based on the summary in table 1, it is evident that there is no research optimizing planning, scheduling and layout for MC in RMS simultaneously. Yet, this is highly beneficial, since layout configuration induces cost and can highly impact the total manufacturing cost. If integrated when optimizing planning and scheduling, the total manufacturing cost including machine configuration cost and system layout configuration cost could be minimized. In addition, the layout configuration required time will impact the makespan (completion time), therefore it is important to consider it simultaneously whith planing and scheduling. This work aims at integrating the three optimization problems by simultaneously answering the following three questions:

1) Which machine in which configuration will take on which operation to produce the selected product modules?
2) In what order these operations will be realized?
3) What is the final RMS Layout?

3. PROPOSED APPROACH

In this paper, our problem formulation is based on the production framework in Figure 4.

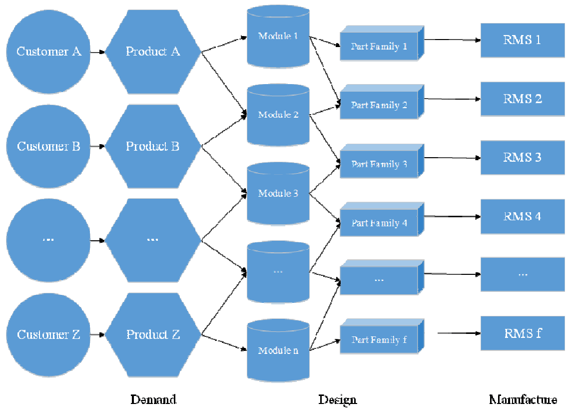

Fig. 4. *Production for RMS*

The procedure for a factory to manufacture mass customized products in RMS is presented in Figure 5. From Figure 5, the information generated from planning, scheduling and layout will affect each other, as follow:

1) Each customer first selects the optional product modules given by the manufacturer to form their product;
2) then they customize these product modules;
3) the manufacturer will collect many customers' orders and decompose each module into parts and components;
4) according to customized properties of each part variant and the optional configuration supported in RMS, manufacturers can generate the relevant production information for process planning, such as the operation sequence for each part variant;
5) orders to process a certain quantity of jobs in RMS will be scheduled in optimal batch clustered from part variants and in optimal processing sequence by integration of production information, optimal layout and other requirements, such as due date;
6) parts and components will be manufactured as the result of planning and scheduling in reconfiguration;
7) the finished part variants will be assembled into a complete customized product and delivered to the customer.

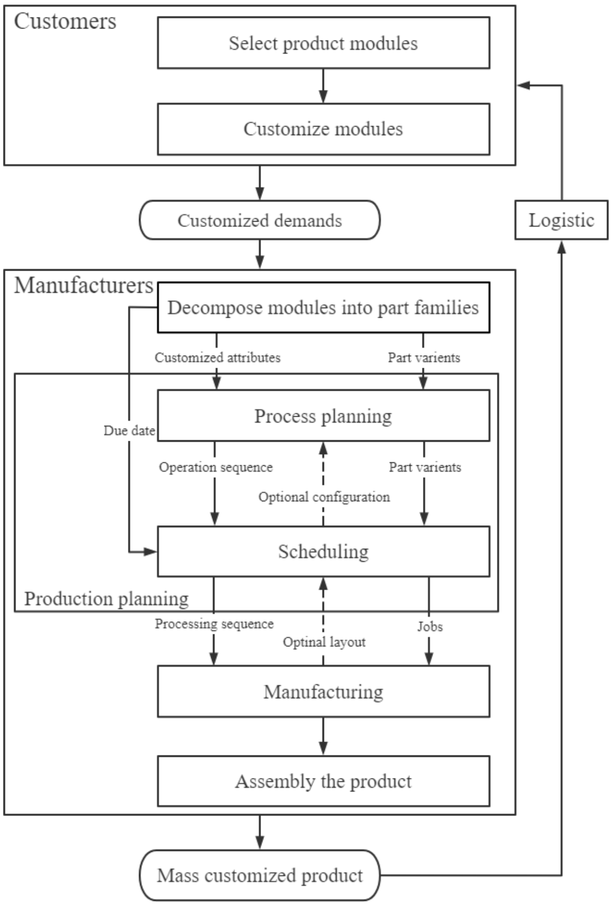

Fig. 5.*Procedure for mass customized products in RMS*

3.1. Problem statement

Let us consider that there are *n* jobs within the same order. These jobs can correspond to different part variants within the same part family. A part variant have several operations to process. In this research, part variants are assumed to differ in two aspects: (1)two part variants have the same operation sequence but different operation processing time. (2) Two part variants have different operation sequence. For example in Figure 6, operation sequence for part variant 1 is different from operation sequence for part variant 2, although they both have operation 2. The whole number of *p* operations for these *n* jobs can be processed in one reconfigurable manufacturing system.

There are *m* machines in this RMS. Each machine has several configurations. For this work, each operation is assumed to be done within only one machine configuration. Each machine can perform several operations.

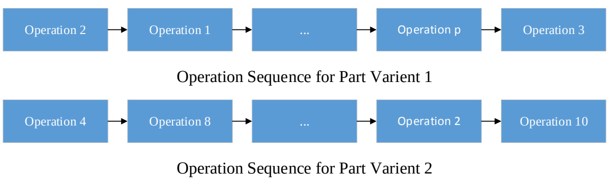

Fig. 6. *Operation sequence for different part variant*

In this problem, processing time and reconfiguration time are considered. The jobs transportation time between two machines is also taken into consideration. Also, we consider that the transportation speed is constant and independent of the jobs, hence the transportation time depends only on the distance.

The scheduling problem is integrated to the RMS layout optimization problem. Due to the fact that it takes time to move Work in Progress (WIP) between equipment, the distance between machines will influence the begining time of each job for a certain operation. Machines are assumed to move only on one of the two X, Y axes. For the purpose of building a linear mathematical model, we consider the distance between two machines is equal to the sum of the distance in X-coordinate and in Y-coordinate between two machines. Each machine has the minimum security distance α_k in X-coordinate and that it β_k in Y-coordinate. As shown in Figure 7, the location of each machine was circled in the center of a gray rectangle, which represents the security area of each machine where the location of any other machine can not exist in. The way to calculate the distance between two machines is also shown in Figure 7. For example to calculate the distance between Machine 2 and Machine 3 , we sum up the distance between Machine 2 and Machine 3 in X-coordinate $\Delta X_{2,3}$ and the distance between Machine 2 and Machine 3 in Y-coordinate $\Delta Y_{2,3}$.

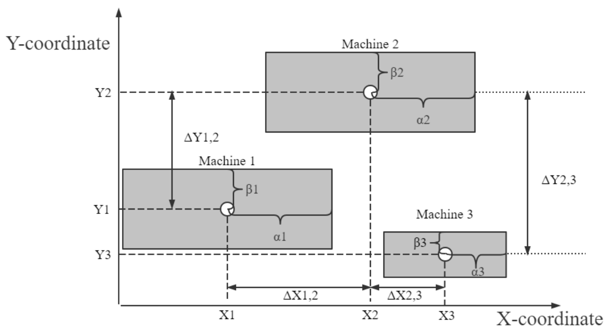

Fig. 7. *The distance between two machines*

3.2. Mathematical model

The indices are as follows:

i, j	Index for job $\{1,2,\ldots,n\}$
c,g	Index for operation $\{1,2,\ldots,p\}$
k,l	Index for machine $\{1,2,\ldots,m\}$

The parameters are as follows:

N	Number of jobs
P	Number of operations
M	Number of machines
$S_{i,c}$	The sequence number for operation *c* of job i
o_num_i	Number of required operations for job i
$o\_mach_m\{\}$	Set of operations that can be processed on machine m
φ_c	Corresponding machine for each operation *c*
$t_{i,c}$	Processing time for operation c of job i
$r_{c,g}$	Reconfiguration time from operation c to operation g , if $c = g, r_{c,g} = 0$

d_i	Due date of job i
U_i	Unit penalty for delay of one time unit of job i
α_k	The minimum security distance for machines k in the X-coordinate
β_k	The minimum security distance for machines k in the Y-coordinate

The goal of this linear mathematical model is to minimize the penalty of all the jobs caused by the tardiness.

The objective function:

$$\text{Minimize } \sum_{i=1}^{n} T_i \times U_i$$

The decision variables are as follows:

$B_{i,c}$	Continuous variable for beginning time of job i for operation c, $B_{i,c} \geq 0$.
$C_{i,c}$	Continuous variable for completion time of job i for operation c, $C_{i,c} \geq 0$.
C_max_i	Continuous variable for final completion time of job i, $C\_max_i \geq 0$.
T_i	Continuous variable for tardiness of job i, $T_i \geq 0$.
X_k	Continuous variable for the X-coordinate of each machine position, $X_k \geq 0$.
Y_k	Continuous variable for the X-coordinate of each machine position, $Y_k \geq 0$.
$\Delta X_{k,l}$	Continuous variable for the distance between each machine in the X-coordinate, $deta\_X_{k,l} \geq 0$.
$\Delta Y_{k,l}$	Continuous variable for the distance between each machine in the X-coordinate, $deta\_Y_{k,l} \geq 0$.

Subject to:

$$C_{i,c} = B_{i,c} + t_{i,c} \qquad \forall i \in \{1,2,\dots,n\}, \forall o_{seq_{i,c}} \neq 0 \quad (1)$$

$$C\_max_i = max(C_{i,c}) \qquad \forall i \in \{1,2,\dots,n\}, \forall c \in \{1,2,\dots,p\} \quad (2)$$

$$T_i = max(C\_max_i - d_i, 0) \qquad \forall i \in \{1,2,\dots,n\} \quad (3)$$

$$\Delta X_{k,l} = \max(X_k\text{-}X_l,\ X_l\text{-}X_k) \qquad \forall k,\ l \in \{1,2,\dots,m\} \quad (4)$$

$$\Delta Y_{k,l} = \max(Y_k\text{-}Y_l,\ Y_l\text{-}Y_k) \qquad \forall k,\ l \in \{1,2,\dots,m\} \quad (5)$$

$$\Delta X_{k,l} \geq \max(\alpha_k, \alpha_l) \qquad \forall k,\ l \in \{1,2,\dots,m\} \quad (6)$$

$$\Delta Y_{k,l} \geq \max(\beta_k, \beta_l) \qquad \forall k,\ l \in \{1,2,\dots,m\} \quad (7)$$

$$B_{i,S_{i,c+1}} \geq C_{i,S_{i,c}} + r_{S_{i,c},S_{i,c+1}} + \delta X_{\varphi s_{i,c}, \varphi s_{i,c+1}} + \delta Y_{\varphi s_{i,c}, \varphi s_{i,c+1}}$$
$$\forall i \in \{1,2,\dots,n\}, \forall c \in \{1,2,\dots,o\_num_i - 1\} \quad (8)$$

$$B_{i,S_{i,c}} + t_{i,S_{i,c}} + r_{S_{i,c},S_{i,g}} \leq B_{j,S_{i,g}} \leq B_{i,S_{i,c}} - t_{j,S_{i,g}} - r_{S_{i,c},S_{i,g}}$$
$$\forall i,j \in \{1,2,\dots,n\}, \forall k \in \{1,2,\dots,m\}, \forall c \in \{1,2,\dots,o_{num_i}\}, g \in \{1,2,\dots,o\_num_j\}, \forall S_{i,c}, S_{i,g} \epsilon o\_mach_k\{\} \quad (9)$$

Constraint (1) defines the completion time of job i for operation c by summing the beginning time of job i for operation c plus the processing time of job i for operation c. Constraint (2) means that the final completion time of job i is the maximum value between all the completion times of job i on all machines. Constraint (3) defines the tardiness of job i. Constraint (4) defines the distance between two machines in the X-coordinate. Constraint (5) defines the distance between two machines in the Y-coordinate. Constraint (6) and (7) restrict separately the distance between two machines as equal to the minimum security distance of those two machines in the X-coordinate and Y-coordinate. Constraint (8) insures that a job cannot begin on a machine before its completion time for the previous operation added to the required machine and layout reconfiguration time and to the job transportation between previous and current machine. Constraint (9) means that on each machine, the beginning time of a job's certain operation cannot be earlier than the sum of any certain operation's completion time for another job and reconfiguration time, and its completion time cannot be later than the difference of any certain operation's beginning time for another job added to reconfiguration time.

3.3. Numerical experiment

This linear mathematical model is tested in the ILOG CPLEX Optimization Studio software developped by IBM company. The version used is V12.10.0.

This numerical experiment is formed of 6 jobs requireing processing. Each job requires 5 operations. The operation sequence and operation time for each job is given in table 2. Table 3 gives the due date and unit penalty for each job.

There are 4 machines. Operations O1 and O5 will be performed on machine1, while operation O2 will be performed on machine2, operation O3 will be performed on machine3, operation O4 will be performed on machine4. The reconfiguration time from O1 to O5 on machine1 is 2, while from O5 to O1 is equal to 4. Between any of two operations performed on different machine, the reconfiguration time is equal to 0.

Table 2. *The operation time for each job*

Job number	Operation in sequence /Operation time				
Job1	O1/1	O2/2	O3/3	O4/4	O5/5
Job2	O5/1	O4/2	O3/3	O2/4	O1/5
Job3	O1/2	O3/4	O5/1	O2/3	O4/5
Job4	O5/4	O3/2	O1/5	O4/3	O2/1
Job5	O2/1	O4/5	O5/4	O3/2	O1/3
Job6	O4/3	O2/2	O1/4	O3/5	O5/1

The minimum security distance machine 1 can accept in X-coordinate and Y-coordinate are both 1. The minimum security distance machine 2 can accept in X-coordinate and Y-coordinate are both 2. The minimum security distance machine 3 can accept in X-coordinate and Y-coordinate are both 3. The minimum security distance machine 4 can accept in X-coordinate and Y-coordinate are both 4.

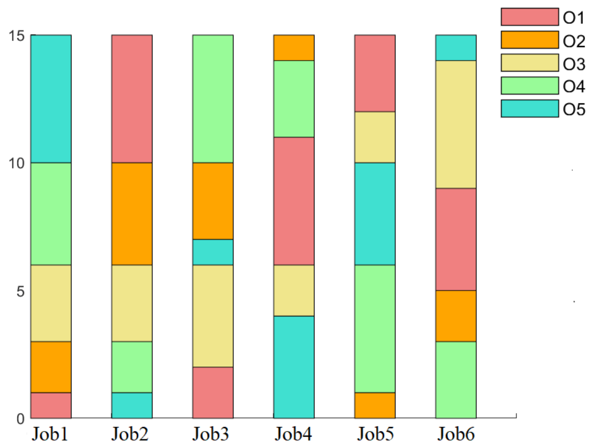

Fig. 8. *The operation sequence for each job*

Table 3. *The due date and unit penalty for each job*

Job number	Due date	Unit penalty
Job1	40	1
Job2	60	2
Job3	10	3
Job4	30	4
Job5	20	5
Job6	50	6

The computation was conducted in a laptop computer powered by an Intel core i7-7600U CPU (2.80 GHz) and 16 GB of RAM. The computing time for this test is close to 2 seconds. The scheduling result for these 6 jobs on each machine is shown in Figure 9.

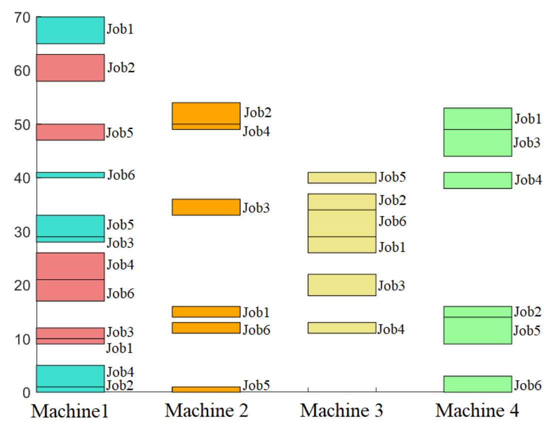

Fig. 9. *The operation sequence for each job*

In this figure, we can find that reconfiguration in machine level always satisfy the time constraints on machine 1 and machine 4. Besides, reconfiguration in system level also satisfy layout constraints between machine 1 and machine 2, or between machine 2 and machine 3. Based on the completion time and due date for each job, we can find that only Job 6 will be delivered on time. The tardiness for Job 1 is 30, the tardiness for Job 2 is 3, tardiness for Job 3 is 39, tardiness for Job 4 is 20, tardiness for Job 5 is 30. This result is basically consistent with the common sense that the greater the unit penalty, the shorter the tardiness.

The machine layout for this task is also given in Figure 10. From this figure, we found that the optimal location of each machine was exactly arranged at the lower right corner of another machine's security area, but different machines' security area may overlap.

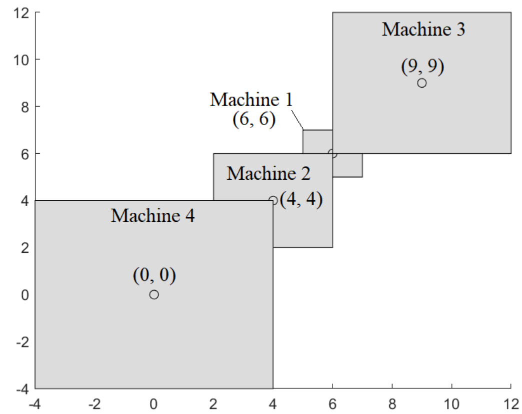

Fig. 10. *The layout of the machines*

4. DISCUSSION

The presented model answers partially the three questions araised at the end of the literature review:

1) Which machine in which configuration will take on which operation to produce the selected product modules? Based on the assumptions that each operation can only be done in one configuration and each configuration can only be achieved on one machine, the proposed model do not really answer this question. Different configurations per machine should be considered, as well as considering that an operation can be processed on different machines with different configurations.
2) In what order these operations will be realized? This question was fully answered in the model.
3) What is the final RMS Layout? The proposed model allows the definition of the optimal machine layout but without considering any restrictions in the space.

In conclusion, the model integrates the three optimization problems but highly simplifies the first problem of machine/configuration determination per operation and slightly simplifies the layout optimization problem.

5. CONCLUSION

This paper presents a first attempt to model the integrated determinstic job shop scheduling problem with machine and layout configuration optimization for RMS by a linear programming mathematical model. A simple numerical experiment is run in the CPLEX software to test the performance of this model. The limits of this work are mainly in the mathematical model. It did not consider the following:

1) jobs within the same part variants that can have different operation sequence;
2) possibility to perform an operation on different machines;
3) setup time (except for changing machine configuration).
4) Cost minimization and other objectives such as environmental impact.

In the future , the above mentioned limits will be integrated as well as other parameters like the availiablity of the reconfigurable manufacturing tools. In addition, this optimization problem is NP-hard, hence, it will not be possible to solve it using CPLEX for bigger examples, hence different metaheuristics should be compared to define the most suited approach to solve this integrated optimization of planning, scheduling and layout configuration for RMS and MC.

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