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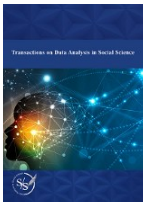

An Operation Planning Model in a Reconfigurable Manufacturing System with Sustainability

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ABSTRACT

There are different forms and modes of the planning problem in complex reconfigurable manufacturing systems (RMS), most of which have primarily focused on the effective and efficient utilization of tools and machine allocation. However, sustainability considerations have often been overlooked in such approaches. This study is designed to introduce a planning model for the operation stages of machining complex products within a factory equipped with a reconfigurable manufacturing system. The primary objective of the proposed model is to enhance system performance while ensuring optimal, low-cost utilization of equipment, machinery, and tools. Unlike traditional planning approaches, this model extends beyond mere production efficiency by integrating sustainability-oriented strategies. Specifically, it incorporates key elements such as reducing energy consumption, minimizing idle time, optimizing operation durations, and improving the processes of tool exchange and replacement. By addressing both operational effectiveness and environmental responsibility, the model provides a holistic framework for planning in RMS environments. Ultimately, the integration of sustainability concepts into reconfigurable manufacturing planning not only contributes to lowering production costs but also strengthens long-term competitiveness and resilience in manufacturing industries, aligning industrial practices with contemporary goals of sustainable development.

1. INTRODUCTION

In recent decades, flexible manufacturing systems have been developed in response to the market diversified demand and have replaced mass production systems in some cases. However, these systems, especially in the United States, have been developed limitedly due to the low investment return as the most important reason [1].Other reasons include complexity, lack of software reliability, the need for highly skilled staff and support costs. To response appropriately to changes in the market demand, we need a new solution that not only consists of Dedicated Manufacturing Line (DML) and Flexible Manufacturing System (FMS), but also has the ability to make quick and

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accurate changes. To this end, we need to design new systems and such systems require a new approach to production with the following abilities [2].

1. Launching a new product and rapid modifications in the production capacity in response to the market demand
2. Rapid integration of new process functions and technologies with the current system
3. Easy compatibility with various amounts of products for regional marketing

Research has begun in the area of reconfigurable manufacturing systems since 1994. These kind of systems are the optimized form of Dedicated Manufacturing Lines (DMLs) and Flexible Manufacturing Systems (FMSs). Thus, they benefit from of both systems advantages. They appear to be the best option when production circulation and production variety are considered simultaneously.

Mehrabi described the aim of the reconfigurable manufacturing system as allowing rapid reforms and modifications in the production capacity and the function of the production system in response to new conditions by rearranging or modifying its components. A reconfigurable manufacturing system is a system originally designed for making rapid changes in the structure as well as in the hardware and software components to be capable of quickly adapting its capacity and function to a family of products [3].

The design of systems and machines is done in RMS in such a way to have a customizable structure, leading to a scalability in both capacity and performance. In RMS, the configurations are designed around a family of products to produce its whole developed family of products. Hence, all products are first grouped and subdivided into sub-families so that each subfamily needs a configuration of the system. The system is configured to produce the first sub-family of products. When completed, the system is configured to generate the second subfamily, and thus to the end.

Figure 1 shows the RMS position versus FMS and DML on two indicators of flexibility and scalability of the product [4].

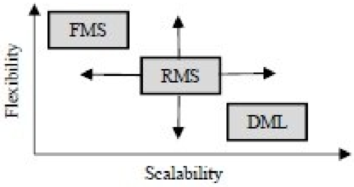

Fig. 1. RMS versus FMS and DML regarding both product flexibility and scalability

In a reconfigurable manufacturing system (RMS), the efficient and optimal use of tools and machinery and planning to reduce production time, cost reduction and sustainability are of great importance. Machining is one of the most important stages in manufacturing. Therefore, the topic of the effective use of machinery and equipment at this stage in a RMS can greatly help to planning in this system and the model provided. The sustainability mentioned can be derived from variables such as power consumed by machines, the cost of energy, the life cycle of the tool, etc.

The term sustainableliterally means life, survival, continuity and what can continue in the future. The sustainability history covers the human-dominated environmental systems from the beginning of civilization to the present time [5], while the energy crisis during 1973 and 1979 showed that the international community has become dependent on renewable energy sources.

The philosophical and analytical framework of sustainability communicates with many of different disciplines and fields so that a science called Sustainability has been developed in recent years [6].Figure 2 represents the domains related to sustainability.

Manufacturing and production is one of the concepts associated with the concept of sustainability nowadays. One of the definitions provided for sustainable production system is the manufacturing of products by processes that minimize environmental negative impacts and at the same time lead to energy and natural resources preservation meanwhile being safe and economical for employees, society and the consumers [7].Figure 3 shows the implications of a sustainable production system.

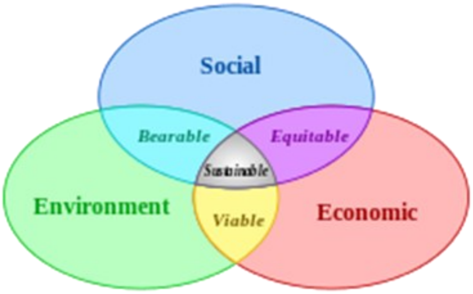

Fig. 2. Sustainability-related areas

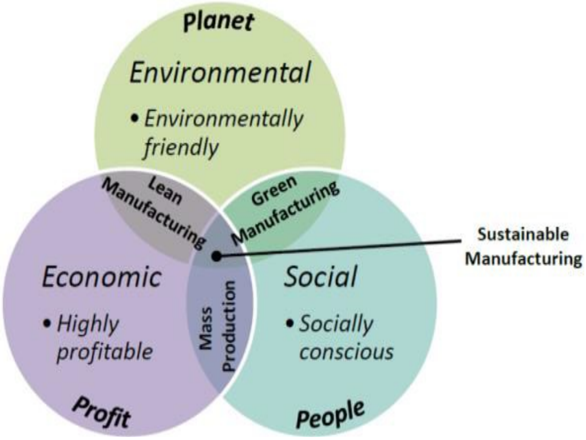

Fig. 3. Concepts of a sustainable production system

2. LITERRATURE REVIEW

Son et al. approach is a design method for RMS and changing the tool with the help of genetic algorithms and similar indicators, which reduces the costs of each step [8].In Tang et al. approach, the activities with reconfiguring production resources capability are shown as active network nodes. Then, the search algorithm for the shortest path in the graph theory is used to search for the optimal path to obtain the best configuration designs [9].

Meng proposed a model for the configuration process of a production system by using the object-oriented colored Petri nets scheduling. This model of object-oriented methods integrate the step-by-step refinement ideas and Petri networks together [10]. Abbasi and Hooshmand studied the use of single-step RMS approach and introduced a methodology that efficiently sets up the systemic scalable and task-oriented production capacities for market demands. They proposed a mixed integer non-linear programming model to determine the lot sizes, corresponding configurations and the optimal order of production tasks. A genetic algorithm-based routine was proposed for solving the model [11]. Lou et al. employed the Dijkstra algorithm to achieve the shortest path for the best system reconfiguration designs although those plans did not consider the configuration of the sources of production and also failed to guarantee the optimal reconfiguration path [12]. Shabaka and Elmaraghy used the kinematic chains to show the relationships between the behavior of manufacturing resources and the mutual constraints of the multiple components. Due to the new configuration needs, the optimal reconfiguration paths could be revealed from the various components of the resources [13]. Azab and Gomaa applied the operation order in the RMS to minimize the cost / time of the change by considering a number of prioritized constraints. They developed correct model as well as another type of canonical genetic algorithm [14]. Bensmaine et al. considered the RMS based on the product characteristics and the capabilities of reconfigurable machines. Their two goals were to minimize the total cost and the total completion time. They proposed a conforming version of the non-dominated sorting genetic algorithm to solve the problem [15]. Musharavati and Hamouda studied the process planning problems at the RMS. They developed the simulated-annealing-based algorithm with the concepts of other algorithms such as knowledge extraction and parallelism [16].

Although there are several articles on RMS and its planning and related modeling, but most of them have the following specifications:

1. They have only considered the timing of the same-family parts and have not regarded the timing of operations and parts.
2. They also have not paid attention to sustainability.
3. The configuration methods presented are mostly simple and several conditions have not been simultaneously considered, and lack a competitive atmosphere and complex relationships.

3. STATEMENT OF PROBLEM

Different modeling approaches have been proposed in a production planning problem for a reconfigurable manufacturing system based on machines and equipment used and the variables associated with this tools and equipment. However, the issue of sustainability has been less considered in these models.

In this research, we focused on the production planning problem of a complex reconfigurable manufacturing system. In particular, we discussed the issues of the effective use of machinery, tools allocation and production planning by considering the concepts related to sustainability to optimize the operation time, energy consumption, tool replacement and direction change times when processing the design specifications.

We planned to develop an operation process scheduling model for the machining of complex products in a typical manufacturing plant. The problem of planning the operation stages involves a large number of issues that need to be addressed in an industry environment. This article attempted to address important issues that will enhance the efficiency of the operation stages planning system in the event of implementation.

The variables in the model are:

Table 1. The variables in the model

Variables			
$\boldsymbol{O_r}$	Number of machining features (operation) in the design features r	C^{idle}	Cost of unemployment and stopping operations per minute
$\boldsymbol{O_r^f}$	First machining feature in design feature r $UMF(1+\sum_{r'}^{r-1} O_{r'})$	C_k	Configuration time rate for k system per minute
$\boldsymbol{O_r^l}$	The latest machining feature in the design feature r $UMF\sum_{r'}^{r} O_{r'}=(O_r^f+O_r\text{-}1)$	C_p^l	The inventory cost of each unit of the product p at the large period t
$\boldsymbol{\sigma_s}$	The design feature determined for the position s of the sequence σ of the design features	C^{Re}	Reconfiguration cost factor for each time running
$\boldsymbol{f_r}$	The mode where the r design feature is located there	C^T	Total production costs
$\boldsymbol{t_o}$	Tool for processing o	CAP_{Ts}	Maximum time capacity at any large period t (hour)
$\boldsymbol{b}$	Maximum time available per time cycle per device	i	Resources list
$\boldsymbol{D_r}$	Total number of processed design characteristics r (demand)	k or l	List of system reconfigurations
$\boldsymbol{h_t}$	Number of slots of the tool occupied by tool t	$m_{p,t}^q$	Demand for product p in period t
$\boldsymbol{H}$	The size of the instrument compartment of each device	s	List of short time periods
$\boldsymbol{NM}$	The upper limit of the total number of authorized devices	$\hat{S}_{(t)}$	The last small time period of the large time period t
$\boldsymbol{ROPN_t}$	Maximum number of possible operations by tool t	t	List of large periods
$\boldsymbol{TO_o}$	Time to process the machining feature O	t_{kl}^{Re}	Time (min) of reconfiguration to change the system between k and l configurations

$\boldsymbol{RT_o}$	Refastening time and reloading time for processing the machining feature o	t^k	Configuration cycle time for k System (min)
$\boldsymbol{TFC_{rr'}}$	Time of changing orientation for face revisit $f_{r'}$ to execute an operation on the r design feature r' from mode $f_r$after completing the operation on the characteristic r	t_s^{idle}	Inaction time in each small period s (hours)
$\boldsymbol{TTC_{oo'}}$	Tool change time t_o after performing o operation by tool $t_{o'}$ while implementing operation o'	T_s	Allocation of small and large periods
$\boldsymbol{C_t}$	If the tool t is loaded: 1, otherwise: 0	$\tau_{\hat{S}_{(t)}}$	End of the last small period s of the large period t
$\boldsymbol{EOR_{rr'}}$	If the direction is changed to execute the operation on the design feature r' after performing the operation on the design feature r located in the mode $f_r$when the design features r and r' toward the machining characteristic o': 1; otherwise: 0	y_p^{max}	Maximum value of product inventory p
$\boldsymbol{Y_{oo'}}$	If after processing the machining feature o by tool t_o, the tool for processing the machining feature o' changes to $t_{o'}$: 1; otherwise: 0	z_{pk}	Product configuration compatibility
$\boldsymbol{X_o}$	If the machining feature o is processed: 1; otherwise: 0	$q_{p,s,k}$	The amount of manufacturing product p in the small period s with the configuration k
$\boldsymbol{Z_r}$	If the feature r is processed: 1; otherwise: 0	τ_s	Small time period s (hours)
$\boldsymbol{\varphi_{kls}}$	Configuration sequence and set member (1 & 0)	δ_{ks}	Configuration index at small period s and set member (1 and 0)
$\boldsymbol{y_t^p}$	Inventory of product p at period t	t_l	Fixed time
$\boldsymbol{N_{UH}}$	Machine cost m	p_a	Certain set-up costs
$\boldsymbol{L}$	Length	D	Diameter
$\boldsymbol{p_o}$	Power consumed by machines	k_l	Energy required for operation
m,n,p,q	Exponents and coefficients of Taylor's relation	Y_E	Energy for each cut
a	Cut depth	t_m	Machining or metal cutting time per operation o
$\boldsymbol{T}$	Lifetime of tool t	E_i	Energy consumed in the overall process i
$\boldsymbol{N_E}$	Cost of energy	T_s	The time of machine that is equal to the total of time of the operation, inaction times, and so on
$\boldsymbol{v_c}$	Cutting speed	N_{OP}	Cost of personnel and manpower
$\boldsymbol{t_{rt}}$	The time required to replace the tool t, which is not suitable for use due to wear or breakdown	N_{FNt}	Cost tool t
$\boldsymbol{C_E}$	Energy price per kilowatt	T_{pap}	Total of failover time and machine inaction time in minutes
$\boldsymbol{P_{PN}}$	Percentage of use of tools	α	Performance
$\boldsymbol{C_{UH}}$	Price of machine m	M_H	Average gross wage of a machine operator
$\boldsymbol{T_C}$	Total time of sub-processes	O_{ZL}	Fixed capital and paying taxes
$\boldsymbol{T_L}$	Life cycle of tool t	N_N	Ineffective cost of machine settings
$\boldsymbol{C_{FN}}$	Tool price	m,C_T	Fixed values dependent on T and v_c
$\boldsymbol{g_{ra}}$	Increased cost to add equipment during reconfiguration operations	ε_i	Impact coefficients
$\boldsymbol{g_{rc}}$	The cost of transporting and relocating equipment during the reconfiguration process	g_{rb}	The cost of removing previous equipment from the device during the reconfiguration process
$\boldsymbol{T_Z}$	Guaranteed time of the axis		

4. MODEL AND METHODOLOGY OF SOLVING

The proposed planning model is as follows:

Objectives :

$$\text{Min: } \sum_{s=1}^{R-1}\sum_{s'=s+1}^{R} TFC_{\sigma(s)\sigma(s')}\, Z_{\sigma(s)}Z_{\sigma(s')}\prod_{k=s+1}^{s'-1}(1-Z_{\sigma(k)}) = \sum_{r=1}^{R}\sum_{r'=1}^{R} TFC_{rr'}EOR_{rr'} \tag{1}$$

Min: $\sum_{o=1}^{O}\sum_{o'=1}^{O} TTC_{oo'}Y_{oo'} + \sum(\frac{t_m}{T})t_{rt} = \sum_{r=1}^{R}\sum_{o=O_r^f}^{O_r^l-1} TTC_{o(o+1)}Z_r + \sum_{r=1}^{R}\sum_{r'=1}^{R} TTC_{O_r^l,O_{r'}^f}EOR_{rr'} + \sum(\frac{t_m}{T})t_{rt}$ (2)

Min: $C^T = \sum_k\sum_l\sum_s \varphi_{kls}\,.\,t_{kl}^{Re}.\,C^{Re} + \sum_p\sum_s\sum_k q_{p,s,k}\,.\,t^k.\,C_k + \sum_p\sum_t C_p^l.\,y_t^p + \sum_s t_s^{idle}.\,C^{idle} + N_{UH}t_l + p_a + N_{UH}\sum_M t_m + N_{OP} + N_N + \sum N_{FNt}$ (3)

Min: $t_l + \sum_M(t_m + TTC_{oo'}\left(\frac{t_m}{T}\right)) + \sum_{r=1}^{R}\sum_{o=O_r^f}^{O_r^l} D_r\,(TO_o + RT_o)$ (4)

Min: $\sum E_i.\,C_E = C_E(p_o t_l + (p_o + k_l v)\sum_M t_m + p_o\sum TTC_{oo'}\left(\frac{\sum_M t_m}{\sum T}\right) + Y_E\left(\frac{\sum_M t_m}{\sum T}\right))$ (5)

Constraints :

$$\varepsilon_1\sum g_{ra} + \varepsilon_2\sum g_{rb} + \varepsilon_3\sum g_{rc} \leq \sum C^{Re} \tag{6}$$

$$\sum_r Z_r \geq 0 \tag{7}$$

$$X_o = Z_r\ :\ \forall r\,,O_r^f \leq O \leq O_r^l \tag{8}$$

$$\sum_{(O:I_{o=I})} X_o \leq M.\,C_t\ :\ \forall t \tag{9}$$

$$\sum_t h_t C_t \leq H \tag{10}$$

$$\sum_{r=1}^{R}\sum_{o=O_r^f}^{O_r^l} D_r(TO_o + RT_o)Z_r + \sum_{r=1}^{R}\sum_{r'=1}^{R} TFC_{rr'}.\,EOR_{rr'} + \sum_{r=1}^{R}\sum_{o=O_r^f}^{O_r^l-1} TTC_{o(o+1)}\,Z_r + \sum_{r=1}^{R}\sum_{r'=1}^{R} TTC_{O_r^f,O_r^l}EOR_{rr'} \leq b.\,NM \tag{11}$$

$$y_{p,1} = y_{p,0} + \sum_{k\in K}\sum_{s\in S_t} q_{p,1,k} - m_{p,1}^q \qquad \forall p \in P, t \in (1) \tag{12}$$

$$y_{p,t} = y_{p,t-1} + \sum_{k\in K}\sum_{s\in S_t} q_{p,s,k} - m_{p,t}^q \qquad \forall t \in (2,T), p \in P \tag{13}$$

$$q_{p,s,k} \geq 0 \qquad \forall p \in P, s \in S, k \in K \tag{14}$$

$$y_{p,t} \geq 0 \qquad \forall p \in P, t \in T \tag{15}$$

$$\sum_{k\in K}\sum_{l\in K} \varphi_{kls}\,.\,t_{kl}^{Re} + \sum_{p\in P}\sum_{k\in K} q_{p,s,k}\,.\,t_k \leq CAP_{Ts}(\tau_s - \tau_{s-1}) \qquad \forall s \in S \tag{16}$$

$$y_t^p \leq y_p^{max} \qquad \forall p \in P, t \in T \tag{17}$$

$$q_{p,s,k}.\,t_k \leq CAP_{Ts}.\,\delta_{ks}.\,z_{pk} \qquad \forall p \in P, s \in S, k \in K \tag{18}$$

$$\sum_{k\in K}\delta_{ks} = 1 \qquad \forall s \in S \tag{19}$$

$$\sum_{k\in K}\sum_{l\in K}\varphi_{kls} = 1 \qquad \forall s \in S \tag{20}$$

$$\delta_{k,s-1} + \delta_{ls} - 1 \leq \varphi_{kls} \qquad \forall k \in K, l \in K, s \in S\backslash\{1\} \tag{21}$$

$$\delta_{k1} = \delta_{k0} \qquad \forall k \in K \tag{22}$$

$$t_s^{idle} = CAP_{Ts}(\tau_s - \tau_{s-1}) - \sum_{k\in K}\sum_{l\in K} \varphi_{kls} \,.\, t_{kl}^{Re} + \sum_{p\in P}\sum_{k\in K} q_{p,s,k} \,.\, t_k \qquad \forall s \in S \tag{23}$$

$$\tau_{\hat{S}_{(t)}} = t \qquad \forall t \in T \tag{24}$$

$$t_m = \frac{\pi DL}{1000 v_c . f} \qquad \forall o \tag{25}$$

$$T = m^{\frac{-1}{n}} v_c^{\frac{1}{n}} f^{\frac{-p}{n}} a^{\frac{-q}{n}} \qquad \forall t \tag{26}$$

$$\left[\left(\frac{\left(\frac{v}{\alpha} \times 1000\right)}{60}\right) \times \left(\frac{c_E}{60}\right)\right] \times T_s = N_E \tag{27}$$

$$\left(\frac{\left(\frac{M_H . O_{zl}}{160}\right)}{60}\right) \times T_s = N_{op} \tag{28}$$

$$\left(\frac{(T_Z - T_{Pap})P_{PN}}{C_{UH}}\right) \times T_s = N_{UH} \qquad \forall m \tag{29}$$

$$\left(\frac{\left(\frac{M_H . O_{zl}}{160}\right)}{60}\right) + \left[\left(\frac{(T_Z - T_{Pap})P_{PN}}{C_{UH}}\right) \times (T_C - T_s)\right] \leq N_N \tag{30}$$

$$C_T . v_c^{-m} = T_L \qquad \forall t \tag{31}$$

$$\frac{T_f}{T_L} = N_{FN} \tag{32}$$

Reducing the orientations time is one of our goals as shown in Figure 1.Relation 2 is to reduce the tool change time. Relation 3 is to reduce the set of production costs, involving reconfiguration, inventory-related process, inaction, etc. Relation 4 seeks to reduce the time of operation, machining and refastening. Relation 5 seeks to reduce energy consumption and associated costs.

Equation 6 represents the costs associated with each reconfiguration. Equation 7 is to ensure the processing of the features. Equation 8 implies that if the designer feature r is selected, all its machining features will be also processed. Equation 9 indicates that the machining feature o is processed and declares the need to the tool. M is a constant representing the upper limit of the tool t allocation to the machining features. In Equation 10, the total number of slots occupied by each machine should not exceed the capacity of the tool slot. Relation 11 suggests that a machine cannot have overloading more than its capacity. Relation 12 involves the inventory for the first planning period, while the relation 13 includes successive large periods. Relations14 and 15 are set to ensure production and inventory levels, and never get negative values. Relation 16 is the total time of reconfiguration and the process, which should be less than the largest work time in any large period. Relation 17 is to create this limitation so that the production and inventory supply of a product will be done to the maximum level. In Equation 18, the manufacturing of a product is possible only when the compatibility occurs between configuration setting and the product. Equation 19 seeks to set a possible and feasible configuration in each small period. Equation 20 also indicates the limitations of reconfiguration, only once in each small period. Relation 21 describes the relationship between the configuration and the sequence index of the configuration. Relation 22 is the start of the configuration for the first planning period. Relation 23 is for calculating the inaction time during small periods. Relation 24 connects each small period to its large period. Equation 25 represents the timing or metal cutting or machining time. Relation 26 indicates the lifetime of the tool. Equation 27 represents the cost of energy, while Equation 28 suggests the cost of personnel and manpower. Relation 29 involves the machines costs, and Equation 30 includes the ineffective cost of machine settings. Equation 31 represents the lifecycle of the tool, and ultimately, Equation 32 reflects the tools related costs.

This model is provided for production planning for complex industrial products by considering the concept of sustainability. Due to the dimensions of the problem, the use of software seems not to be so fit. Thus, the meta-innovative algorithms can be used to solve the model.

5. CONCLUSION

Since both FMS and DML systems have serious defects due to not supporting a variety of products, their high production costs, etc., then, we need another solution, which is the use of the RMS system. On the other hand, sustainable production is associated with the effectiveness of production processes. There are various ways to improve the sustainability of production. We need to identify different parameters to implement the concept of sustainability. The identified input parameters included the cutting speed, feed rate and total volume of material harvested. The output parameters were surface roughness, process length, and the processing cost.

Our model introduces a new approach to the allocation of tools and the device loading components for RMS planning problems by considering sustainability. It provides a method to optimize the tool switching time and change the direction, reduce the cost and optimize the energy.

Our research suggests that failure to test problems at real and industrial scales will create some limitations. Put it more accurately, further studies in this area should be done in future.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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