An Operation Planning Model in a Reconfigurable Manufacturing System with Sustainability

F. Asgari1*, M. Sargazi2

1 Department of industrial engineering, Tehran Science and Research Branch, Islamic Azad University, Tehran, Iran
2 Department of industrial engineering, Tehran Science and Research Branch, Islamic Azad University, Tehran, Iran

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ABSTRACT

There are different forms and modes of the planning problem of a complex reconfigurable manufacturing system (RMS), most of which have targeted the effective and efficient use of tools and machine allocation and rarely addressed the sustainability concepts. This study was designed to provide a planning model of operation stages for machining complex products at a factory with a reconfigurable manufacturing system aimed at increasing the system performance and optimal and low-cost utilization of equipment’s, machinery and the tools. In addition to considering the effective use of tools, allocation of machines and production planning, the concepts related to sustainability in reducing energy consumption, optimizing the duration of operation, tool exchange and replacement, etc. are also considered in this model.

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 respond 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 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 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 subfamilies 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].

![Figure 1. RMS versus FMS and DML regarding both product flexibility and scalability](image)

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 sustainableness literally 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.
2. LITERATURE 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>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_r$</td>
<td>Number of machining features (operation) in the design features $r$</td>
</tr>
<tr>
<td>$O_{fr}$</td>
<td>First machining feature in design feature $r$</td>
</tr>
<tr>
<td>$O_{lr}$</td>
<td>The latest machining feature in the design feature $r$</td>
</tr>
<tr>
<td>$\sigma_s$</td>
<td>The design feature determined for the position $s$ of the sequence $\sigma$ of the design features</td>
</tr>
<tr>
<td>$f_r$</td>
<td>The mode where the $r$ design feature is located there</td>
</tr>
<tr>
<td>$t_o$</td>
<td>Tool for processing $o$</td>
</tr>
<tr>
<td>$h_t$</td>
<td>Number of slots of the tool occupied by tool $t$</td>
</tr>
<tr>
<td>$H$</td>
<td>The size of the instrument compartment of each device</td>
</tr>
<tr>
<td>$NM$</td>
<td>The upper limit of the total number of authorized devices</td>
</tr>
<tr>
<td>$R_O P_N_t$</td>
<td>Maximum number of possible operations by tool $t$</td>
</tr>
<tr>
<td>$T O_o$</td>
<td>Time to process the machining feature $O$</td>
</tr>
<tr>
<td>$\mathcal{L}_{idle}^k$</td>
<td>Cost of unemployment and stopping operations per minute</td>
</tr>
<tr>
<td>$\mathcal{C}_k$</td>
<td>Configuration time rate for k system per minute</td>
</tr>
<tr>
<td>$\mathcal{C}_p$</td>
<td>The inventory cost of each unit of the product $p$ at the large period $t$</td>
</tr>
<tr>
<td>$\mathcal{C}_{Re}$</td>
<td>Reconfiguration cost factor for each time running</td>
</tr>
<tr>
<td>$\mathcal{C}_T$</td>
<td>Total production costs</td>
</tr>
<tr>
<td>$\mathcal{C}_{PA}$</td>
<td>Maximum time capacity at any large period $t$ (hour)</td>
</tr>
<tr>
<td>$S(t)$</td>
<td>The last small time period of the large time period $t$</td>
</tr>
<tr>
<td>$m_{p,t}$</td>
<td>Demand for product $p$ in period $t$</td>
</tr>
<tr>
<td>$t$</td>
<td>List of large periods</td>
</tr>
</tbody>
</table>

Table 1. The variables in the model
The proposed planning model is as follows:

**Objectives:**

\[ \text{Min:} \quad \sum_{s=1}^{R} \sum_{t=1}^{R} T \sum_{i=1}^{R} \sum_{j=1}^{R} T F C (a_{i}) (i \sigma_{j}) (j \sigma_{k}) \prod_{k=s+1}^{R} (1 - Z_{s}(k)) = \sum_{s=1}^{R} \sum_{i=1}^{R} T F C (s) E O R (s) \]

**4. MODEL AND METHODOLOGY OF SOLVING**

The proposed planning model is as follows:

- **Objectives:**

  \[ \text{Min:} \quad \sum_{s=1}^{R} \sum_{t=1}^{R} T \sum_{i=1}^{R} \sum_{j=1}^{R} T F C (a_{i}) (i \sigma_{j}) (j \sigma_{k}) \prod_{k=s+1}^{R} (1 - Z_{s}(k)) = \sum_{s=1}^{R} \sum_{i=1}^{R} T F C (s) E O R (s) \]
Min: \[ \sum_{t=0}^{r} \sum_{d=0}^{f} \text{TTC}_{0t} \cdot Y_{n0t} + \sum_{t=0}^{r} \sum_{d=0}^{f} \text{TTC}_{0(t+1)} \cdot Z_{r} + \sum_{t=0}^{r} \sum_{d=0}^{f} \text{TTC}_{o1t} \cdot EOR_{r+} + \sum_{t=0}^{r} \sum_{d=0}^{f} \text{TTC}_{m1t} \cdot EOR_{r+} \]

Min: \[ C^{T} = \sum_{i=1}^{s} \sum_{j=1}^{k} \varphi_{k_{i}} \cdot t_{k_{i}} \cdot C^{R_{i}} + \sum_{p=1}^{n} \sum_{s=1}^{m} \sum_{k=1}^{n} q_{p,s,k} \cdot t^{k} \cdot C_{k} + \sum_{p=1}^{n} \sum_{s=1}^{m} \sum_{k=1}^{n} t^{k}_{s} \cdot \gamma_{p} \cdot C^{p} + \sum_{t=1}^{m} \text{idle} \cdot C^{idle} + N_{idle} \cdot t \]

Min: \[ t_{r} + \sum_{h=0}^{T} \text{TTC}_{0h} \left( \frac{t_{r}}{T} \right) + \sum_{r=0}^{R} \sum_{a=0}^{f} D_{r} (T_{0} + R_{T}) \]

Min: \[ \sum_{E_{r}} C_{E} = C_{E} (p_{o} \cdot t_{1} + (p_{b} + k_{v}) \cdot m_{t} + p_{o} \cdot \text{TTC}_{0o} \left( \frac{\text{m}_{p} \text{m}_{o}}{T_{o}} \right) + Y_{E} \left( \frac{\text{m}_{p} \text{m}_{o}}{T_{o}} \right) \]

Constraints:

\[ \varepsilon_{1} \sum g_{ra} + \varepsilon_{2} \sum g_{rb} + \varepsilon_{3} \sum g_{rc} \leq \sum C^{R_{e}} \]

\[ \sum_{r} Z_{r} \geq 0 \]

\[ X_{a} = Z_{r} : \forall r, O_{r} \leq O_{l} \]

\[ \sum_{t} X_{a} \leq M \cdot C_{r} : \forall t \]

\[ \sum_{r=1}^{R} \sum_{a=0}^{f} D_{r} (T_{a} + R_{T}) Z_{r} + \sum_{r=1}^{R} \sum_{s=1}^{T} TFC_{0r} \cdot EOR_{r+} + \sum_{r=1}^{R} \sum_{a=0}^{f} \text{TTC}_{0r} \cdot EOR_{r+} \leq h \cdot N \]

\[ y_{p,1} = y_{p,0} + \sum_{(K \in S_{r})} q_{p,1,k} - m_{p,1} \quad \forall p \in P, t \in (1) \]

\[ y_{p,2} = y_{p,1} + \sum_{(L \in S_{r})} q_{p,s,k} - m_{p,2} \quad \forall t \in (2, T), p \in P \]

\[ q_{p,s,k} \geq 0 \quad \forall p \in P, s \in S, k \in K \]

\[ \sum_{K \in S_{r}} \phi_{k_{s}} \cdot t_{k_{s}} \leq \text{CAP}_{r} (T_{r} - T_{r-1}) \quad \forall S \in S \]

\[ y_{p}^{T} \leq y_{p}^{\text{max}} \quad \forall p \in P, t \in T \]

\[ q_{p,s,k} \leq \text{CAP}_{r} \cdot \delta_{k_{s}} \cdot T_{p} \quad \forall p \in P, s \in S, k \in K \]

\[ \sum_{K} \delta_{k_{s}} = 1 \quad \forall s \in S \]

\[ \sum_{K} \varphi_{k_{s}} = 1 \quad \forall s \in S \]

\[ \delta_{k_{s-1}} + \delta_{k_{s}} - 1 \leq \varphi_{k_{s}} \quad \forall k \in K, l \in K, s \in S \backslash (1) \]
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. Relations 14 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.

\[
\begin{align*}
\delta_{k1} &= \delta_{k0} \quad \forall k \in K \\
\tau_{s} &= \tau_{s-1} - \sum_{k \in K} \sum_{i \in K} \phi_{k1} - \phi_{k1}^{Re} + \sum_{p \in P} \sum_{k \in K} q_{p,k} \cdot t_{k} \quad \forall S \in S \\
\tau_{S(t)} &= t \quad \forall t \in T \\
t_{m} &= \frac{\pi DL}{1000 \nu_c \cdot f} \quad \forall o \\
T &= m + \frac{1}{\nu_c} \frac{\pi}{\nu_c} \frac{\pi}{\nu_c} \\
\left[ \frac{(\nu \times 1000)}{60} \right] \times \left[ \frac{c_{E}}{60} \right] \times T_{s} &= N_{E} \\
\left( \frac{(T_{Z} - T_{Pap})P}{C_{UH}} \right) \times T_{s} &= N_{op} \\
\left( \frac{(T_{Z} - T_{Pap})P}{C_{UH}} \right) \times (T_{C} - T_{s}) &\leq N_{UH} \\
C_{T} \cdot v_{c}^{m} = T_{L} \quad \forall t \\
T_{F} \cdot T_{L} &= N_{FN}
\end{align*}
\]
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 provide 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.

REFERENCES


