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Service Level as Performance Index for Reconfigurable Manufacturing System Involving Multiple Part Families

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Abstract

In this global manufacturing era, one of the important challenges faced by manufacturer is how to deal with stochastic demand and ever changing customer needs and requirements. Reconfigurable manufacturing systems are recognized as next generation manufacturing systems capable of providing the exact functionality and capacity as and when required. Some important performance indices studied in the past include cost, ease of reconfigurability, productivity, reliability and availability for assessing the performance of these systems. The economics while carrying out the reconfiguration process of these systems must include parameters such as cost incurred while producing orders of part families on a particular configuration and the reconfiguration cost associated while changing over from initial configuration to another. The complexity and cost involved from changing one configuration to another depends on the existing initial configuration and the new configuration required for subsequent production. In this paper, based on the different efforts associated with the reconfiguration process, a new index of performance termed as "Service Level" is proposed. The proposed indicator is modeled for a multiple part family reconfigurable manufacturing system. The methodology proposed is explained using a numerical example. The results obtained along with their important implications were discussed.

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Keywords: Reconfigurable manufacturing system; part families; service level; performance index

1. Introduction

The present manufacturing scenario is characterized by several market variables like unpredictable demand, short product life-cycles, customized products, and rapid changes in the process technology. These market variables have

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forced the manufacturers to adapt the changing requirements efficiently and effectively. These modern challenges have paved the way for the new manufacturing paradigm known as a Reconfigurable Manufacturing System (RMS). An RMS is defined as a manufacturing system capable of rapid changes in structure, as well as in hardware and software components, in order to quickly adjust to the dynamic demands of the manufacturing system governed by market requirements [1]. The concept of RMS is similar to the concepts of modular manufacturing [2], component based manufacturing systems [3-5], modular product system [6], and modular flexible manufacturing [7]. The core characteristics of RMSs are modularity, Integrability, convertibility, diagnosability, and customization [8]. The design, implementation and operation of any RMS revolve around part families. The effectiveness of any RMS can be best judged by the number of part families which can be produced within this system after suitable reconfiguration of the system. The reconfiguration process of the system can be classified into physical reconfiguration and logical reconfiguration [9]. Examples of physical reconfigurations include layout reconfiguration, adding or removing of machines, tools or components, and material handling system reconfiguration. While, examples of logical reconfiguration includes, re-programming of machines, re-planning, re-scheduling, re-routing, and increasing or decreasing shifts or the number of workers.

Nomenclature

N	number of stages on the product line
L	number of part families
M_i	reconfigurable machine, where i=1,2,3......N
$C_{initial}$	initial product flow line configuration
φ_i	number of feasible options by which initial configuration $C_{initial}$ can be converted into desired configuration for an upcoming part family, where, i=1,2,3......
α_{ij}	reconfiguration effort index (RcEI) for i^{th} machine to be converted into j^{th} machine
β_i	adding effort index (AEI) associated with i^{th} machine
γ_i	removal effort index (RmEI) associated with i^{th} machine
η_i	re-adjustment effort index (RjEI) associated with i^{th} machine
M_{rg}	effort matrix for reconfiguration of machines
M_{add}	effort matrix for adding machines
M_{rem}	effort matrix for removing machines
M_{radj}	effort matrix for re-adjustment of machines
m	number of machines removed on the flow line for upcoming configuration
n	number of machines re-adjusted on the flow line for upcoming configuration
p	number of machines re-configured on the flow line for upcoming configuration
q	number of machines added on the flow line for upcoming configuration
$R_{effort}^{\varphi_i}$	reconfiguration effort while reconfiguring initial configuration C initial to new configuration φ_i
ψ_i	service level index for i^{th} part family

The term "part family" or "product group" has been defined in British Standard BS 5191 as 'a number of products with one or more common characteristics, which is convenient to combine them for planning and control processes'. Grouping of products can be considered as a requirement for RMS design in order to facilitate the production of variants products, material purchase and production management [10]. Though, the definition of the RMS by Koren [1] was only confined to single part family. But later, in contrast to this, Xiaobo [11] described an RMS as a manufacturing system in which a variety of products required by customers can be classified into families, each of which is a set of similar products, corresponds to one configuration of RMS. Also, multiple part families aspect to RMS design and operation was studied till recently by Hasan et al. [12]. The most widely used approaches for grouping products into part families are the ones developed by Askin [13] and Suresh [14]. These approaches were based on cell formation in which machine and parts were prior identified. The technique developed by Ratchev [15] employed a fuzzy clustering approach for cell formation which was aimed at selecting an optimum shop floor configuration. Heragu and Gupta [16], Kim [17] used mathematical programming approaches to optimize system configuration based on part mix for formation of part families. Several researches used quadratic programming for cell formation [10, 18, 19]. Abdi and Labib [10] proposed an AHP approach for part families formation for an RMS. Detailed work was also done by Rakesh [20] for part families formation in an RMS based on hierarchical clustering approach.

The process of designing and subsequent operation of an RMS starts with the classification of products into part families. Subsequently, the manufacturer has to decide suitable configuration which may be initially adapted for production of parts belonging to a part family if an entirely new product flow line facility is to be setup. However, in a realistic case, there may exists some initial flow line configurations which were prior operated to produce jobs as per the production requirements. In order to produce jobs for subsequent part families these initial product flow lines may be reconfigured to suit the requirements of the future product families. The basic aim of the reconfiguration strategy is to carry out the process in an optimized way. This reconfiguration may be in the form of adding or removing machines, re-adjustment of machines, adding new machines or reconfiguring some machines for capacity or operational requirements. For any given initial product flow line, there may exists several alternatives which may be adapted to reconfigure an existing line into a new product flow line for a desired part family. Thus, it is necessary that the selection of alternative should be based on some criterion which must take into account factors associated with the changeover of this initial configuration to a new configuration. The literature reviewed on the topic revealed that most of the work on RMS takes into consideration single part family and performance indicator of service level has not been taken up in detail. Motivated by these gaps the present study is focused to address the issue of the service level for part families which may be taken as a performance measure indicator for RMS. The proposed methodology is explained by using an example, the details of which are summarized in the following sections.

1.1. Reconfigurable Product Flow Line (RPFL)

A simple product flow line is basically arrangement of some station or stages on which some desired operations are carried out. These stations or stages are basically work centers comprising of some machine(s). On the other hand, a reconfigurable product flow line can be defined as a production or manufacturing facility composed of reconfigurable machines, the configuration of which can be changed as per the requirement. The reconfiguration may be carried out either by adding or removing machine(s) from the product line, re-adjusting existing machines on various stages or stations and by reconfiguring some machines to suit the new requirements. A RPFL can be reconfigured to suit the product requirement as and when needed. Jobs move from one stage to subsequent stages as per the required operation sequence and finally a finished product may be obtained after it passes the last stage on the product line. A schematic diagram of a product flow line is shown in Fig.1.

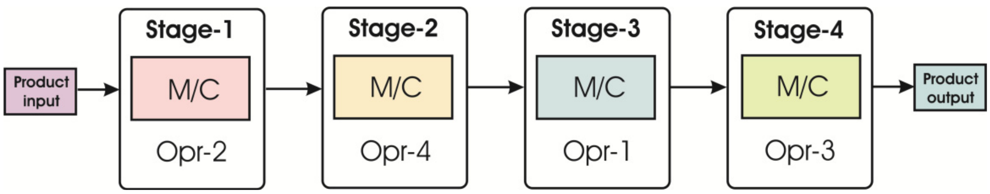

Fig. 1. Schematic block diagram for a product flow line.

1.2. New Index for Performance

The main focus of modeling any RMS is based on optimization of certain variables to carry out the reconfiguration process. Most of the researches on RMS take into account the objective of reduction in cost and reconfiguration effort required for this change in configuration. These optimization problems are based on linear programming models, neural networks, nature inspired algorithms and many other operation research based techniques. Literature reviewed revealed that most of the reconfigurations problems are based on RMSs involving single part family. Though, Xiaobo [11, 21] proposed a framework for a stochastic model of an RMS which involves measuring the performance based on the service level. In another work, Goyal [22] developed reconfigurability index for reconfigurable machine tools based on set theory. In summary, it can be said that reconfigurable manufacturing systems offer several feasible alternative product flow line configurations for producing a product part family over some period demand and when the product family changes a corresponding change in product line configuration is required. Therefore, the problem of calculating a cumulative effort in terms of some index is required when an initial product flow line configuration is changed into other configurations required to produce multiple part families. In the present investigation, a novel methodology is suggested to develop a service level index for part families for RMS. The index of service level is based on the cumulative effort required to reconfigure an existing flow line configuration to a new configuration as desired to produce jobs belonging to an entirely different family of products. The index proposed takes into consideration the various efforts which are required in, adding or removing any machine from product flow line, rearrangement of some machines on various stages of the line based on operation precedence required by the product family and the reconfiguration of the machines itself to take advantage of their multiple operational capability and capacity.

2. Problem Formulation

The reconfigurable product flow line allows quick changes in its configuration in response to changes in the product mix as classified by distinct part families. Here, it is important to evaluate the degree of reconfiguration effort required to handle multiple part families through the process of reconfiguration of an existing flow line configuration. The authors propose a new performance measure index for flow line reconfiguration based on the efforts required to carry out this change. The proposed index gives an insight about the effort required to change an existing product line configuration to a new configurations required for multiple part families. For modeling the problem, the following assumptions are used.

2.1. Assumptions

- Various products to be manufactured are classifiable into distinct part families.
- Initial configuration of the product flow line is composed of at-least of 2 stages with a single reconfigurable machine (M_i) at each stage.
- Each machine can be reconfigured into any other type of machine as per requirement.
- Reconfiguration effort index is same either when i^{th} machine is reconfigured into j^{th} machine or j^{th} machine is reconfigured into i^{th} machine, i.e. same effort index values when M_1 is reconfigured to M_2 and vice versa.
- A machine can be added, removed, reconfigured or re-adjusted while modifying the flow line configuration from any initial configuration to the desired configuration required for a part family. i.e. any machine cannot be reconfigured and re-adjusted simultaneously.
- Reconfiguration effort is considered to be the highest, followed by addition effort, removal effort and re-adjustment effort. i.e. $\alpha_{ij}<\beta_i<\gamma_i<\eta_i$.
- The various effort indices are independent of the product flow line stages.
- Time required for changing from one configuration to another is not considered.

3. Development of Performance Index

For the development of performance index based on service level of part families in a multi-part family RMS the following four different types of effort are considered. These efforts are required to change an initial flow line configuration to a new configuration capable of handling a new part family.

Addition Effort: This effort is required to add a new machine on any stage of the product flow line. This effort is measured as an index denoted by β_i which may be termed as “Adding Effort Index (AEI)”. For example, adding effort of machine M_1 is 0.4 while for machine M_2 is 0.2, it means that more effort is required to add machine M_1 on the flow line as compared to M_2. The various adding efforts associate with various machines are present in a matrix denoted by $M_{add}=[\beta_i]$.

Removal Effort: This effort is required to remove any machine from an initial flow line configuration. The measurement index associated with this effort is denoted by γ_i. This effort may be termed as "Removal Effort Index (RmEI)". As an example, the effort required to remove machine M_3 (γ_3=0.4) is more than the effort required to remove machine M_4 (γ_4=0.3). The removal efforts indices associated with various machines are denoted by matrix $M_{rem}=[\gamma_i]$.

Readjustment Effort: This is the effort related to the readjustment of machines on various stages of the flow line, if required. This rearrangement is necessary to fulfill the operation precedence's of the jobs. For illustration, say for any initial flow line configuration, stage-1 comprised of machine M_4 for operation say turning; stage-2 comprised of machine M_2 for operation say drilling and machine M_3 is installed on stage-3 for operation say reaming. Now, if a new configuration is required for a part family on which the sequence of operation is say milling, turning and boring on stages-1, 2 and 3 respectively. It implies that now machine M_4 is to be readjusted on stage-2, thus the effort required for this readjustment is termed as re-adjustment effort index (RjEI). This readjustment is important to reduce the transportation time, back tracking and smooth flow of jobs on the flow line. This effort is denoted by η_i and complete re-adjustment matrix is presented by $M_{radj}=[\eta_i]$.

Machine Reconfiguration Effort: One of the distinguishing characteristic of RMSs are Reconfigurable Machine Tools (RMTs). These RMT are modular machines having customized operational capability and capacity. The basic structure of these machines can be altered to have varied capacity and operational capabilities. The reconfigurable machine tools are developed as modular machines comprising different modules [1, 23, 24]. In the present paper, the term "Machine" is synonymous with RMT. The Machine Reconfiguration Effort (ReEI) is defined as the effort required in changing the operational capability of these machine. The machine reconfiguration index is presented by α_{ij}. For illustration, α_{23} present the effort required to change the operational capability of Machine M_2 to machine M_3. The complete reconfiguration effort matrix is shown by $M_{rg}=[\alpha_{ij}]$.

The various effort indices defined above can be calculated by taking factors such as cost, number of modules added/removed/adjusted for converting an RMT, space constraints etc. Recently, work has been done by Goyal [21] to calculate the reconfigurability index of reconfigurable machines. Though no literature has been found with suggest some model or expressions to calculate other indices associated with removal, addition or re-adjustment of machines which carrying out the flow line reconfiguration. In the present work, the various indices are assumed randomly. In order to calculate the total reconfiguration effort required to change an existing initial configuration $C_{initial}$ to some new configuration on which jobs belonging to an upcoming part family can be processed. In order to realize this reconfiguration process, say, 'm' number of machines are to be removed from initial product line, 'n' number of machines needs to be readjusted and 'p' number of machines are to be reconfigured and "q" number of new machines are required to be added. Thus, the effort involved in this reconfiguration can be calculated as

$$R^{i}_{effort}=\sum_{j=1}^{m}\gamma_j+\sum_{k=1}^{n}\eta_k+\sum_{l,m=1}^{p}\alpha_{lm}+\sum_{i=1}^{q}\beta_i \tag{1}$$

For i^{th} part family the service level ψ_i can be calculated as

$$\psi_i=\frac{\phi_i}{\sum_{j=1}^{\phi_i}R^{j}_{effort}} \tag{2}$$

4. Illustrative Example

Consider an RMS, to be configured for 3 part families (L=3) with Machines M_1, M_2, M_3 and M_4. The various effort matrices are as follows

$$M_{add} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 \\ 0.4 & 0.2 & 0.4 & 0.3 \end{bmatrix}$$

$$M_{rem} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 \\ 0.3 & 0.2 & 0.4 & 0.3 \end{bmatrix}$$

$$M_{radj} = \begin{bmatrix} M_1 & M_2 & M_3 & M_4 \\ 0.2 & 0.1 & 0.3 & 0.2 \end{bmatrix}$$

$$M_{rg} = \begin{bmatrix} \text{From}/\text{To} & M_1 & M_2 & M_3 & M_4 \\ M_1 & - & 0.7 & 0.8 & 0.6 \\ M_2 & - & - & 0.9 & 0.7 \\ M_3 & - & - & - & 0.8 \\ M_4 & - & - & - & - \end{bmatrix}$$

Initial Flow line configuration, $C_{initial}$ and the various new configurations required for part families-1, 2 and 3 are shown in Figure-2.

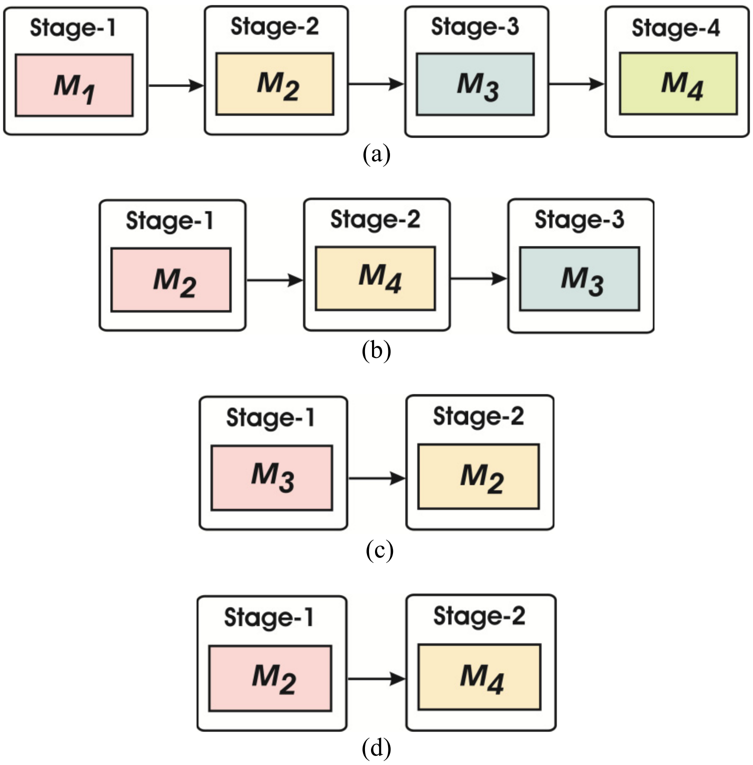

Fig. 2. Flow line configurations (a) initial configuration, $C_{initial}$, (b) for part family-1, (c) for part family-2, and (d) for part family-3.

For illustration, consider part family-1, the initial configuration $C_{initial}$ can be converted into new a configuration φ_1 by removing machine M1 from stage-1, re-adjusting machines M_2, M_3, M_4 to stages-1, 2 and 3 respectively. The effort for this reconfiguration of the product flow line is calculated using equation (1) as

$$R^{j}_{effort} = \sum_{j=1} \gamma_j + \sum_{k=2,3,4} \eta_k \quad (3)$$

Similarly, the efforts required other configuration φ_2, φ_3, φ_4, φ_5, φ_6 and φ_7 can be calculated. Finally, the service level for part family-1 is calculated as below using equation (2)

$$\psi_i = \frac{7}{(0.9+1.7+1.0+1.3+2.6+1.5+1.9)} \quad (4)$$

Possible alternatives which can be adapted to reconfigure initial flow line configuration, $C_{initial}$ to the configuration required for the three part families considered along with effort and service level values are presented in Table-1.

Table 1. Results for service level values ψ_i obtained for the RMS considered.

		Add	Remove	Re-adjust	Reconfiguration of RMTs	R^{i}_{effort}	ψ_i
Part Family-1	φ_1	-	M_1	M_2, M_3, M_4	-	0.9	0.64
	φ_2	-	M_4	-	M_1 to M_2, M_2 to M_4	1.7	
	φ_3	-	M_4	M_2	M_1 to M_4	1.0	
	φ_4	-	M_2	M_3, M_4	M_1 to M_2	1.3	
	φ_5	-	M_3	-	M_1 to M_2, M_2 to M_4, M_4 to M_3	2.6	
	φ_6	-	M_3	M_2, M_4	M_1 to M_3	1.5	
	φ_7	-	M_1	-	M_3 to M_4, M_4 to M_3	1.9	
Part Family-2	φ_1	-	M_3, M_4		M_1 to M_3	1.4	0.67
	φ_2	-	M_1, M_4	M_2, M_3	-	1.0	
	φ_3	-	M_1, M_2	M_3	M_4 to M_2	1.5	
	φ_4	-	M_2, M_3	-	M_1 to M_3, M_4 to M_2	2.1	
Part Family-3	φ_1	-	M_1, M_3	M_2, M_4	-	1.0	0.59
	φ_2	-	M_3, M_4	-	M_1 to M_2, M_2 to M_4	2.1	
	φ_3	-	M_1, M_2	M_4	M_3 to M_2	1.6	
	φ_4	-	M_2, M_4	-	M_1 to M_2, M_3 to M_4	2.0	

5. Result and discussion

The developed index of service level, ψ_i gives fairly reasonable idea about the effort needed to reconfigure any initial flow line configuration $C_{initial}$ to a new configuration required for any part family. The developed index of service level may be taken as a function of two parameters, one associated with the reconfiguration effort value R^{i}_{effort} and the other related to number of possible alternatives φ_i by which this change in existing configuration can be achieved. The relationship between ψ_i, R^{i}_{effort} and φ_i is that ψ_i is directly proportional to φ_i while it is inversely proportional to R^{i}_{effort}. This proportionality is quite justifiable, as higher the reconfiguration effort means low service level and higher the number of alternatives by which this reconfiguration is can be achieved, higher will be the service level. The results obtained for the example considered clearly demonstrates the above relationships. In the example, based on the initial configuration highest service level is obtained for part family-2 (ψ_2=0.67) and a minimum service level of 0.59 is obtained for part family-3 (ψ_3). A simple interpretation of this is that changing the initial configuration to the new configuration is easier as for part family-2 as compared to part family-3. Though, the present work is just a preliminary work for establishing the service level index of part families as a performance indicator of reconfigurable manufacturing systems. In literature, nearly no study was found which takes into account this kind of measure. This physical relevance and implications of study is that the manufacturer can get an insight as to which the present configuration of the flow line should be changed to get maximum benefit out of it. Further, this also enables the manufacturer to assess the relevant importance given to each part family. Also, if there are multiple existing flow line configurations, which configuration can be changed to which new configuration in order to have maximum performance of the system.

6. Conclusion

The developed index of service level can be taken as one of the performance indicators of RMS. The developed service level index gives a basic insight of how performance evaluation of reconfiguration efforts may be dealt for RMS involving multiple part families. The finding may be useful in situations where there exist multiple initial flow line configurations which can be reconfigured for upcoming part families. Under multiple initial configurations the service level index helps in reconfiguring only that initial configuration to a new one which gives higher values of the proposed index for various new part families which requires a new configuration for their processing. Since, the index developed is based on various assumptions, thus a better index can also be worked out in future incorporating many other parameters which are simply assumed in this study. Some methodology may be proposed to calculate indices like addition effort, removal effort and re-adjustment efforts which are arbitrary assumed in the present work. Further, the study can be replicated to include optimization as well.

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