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Responsiveness and Economy Indicators for Reconfigurable Manufacturing System

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Abstract - **Reconfigurable manufacturing system is the new manufacturing paradigm offering exact functionality and capacity as and when required. The Reconfigurable Machine Tool (RMT) plays a pivotal role in the accomplishment of this objective through their built in modular structure consisting of basic and auxiliary modules along with the open architecture software. Optimally assigning machines in the RMS based on cost only leads to the higher reconfiguration effort required in the later stages. Thus in past couple of years novel performance measures have been proposed to assess the expected performance of the system to counter the volatility and severe fluctuations in the product types and their volumes. These all manufacturing traits which measure the various attributes of RMS to react to the changes are categorized in the present work as responsiveness parameters and yet another set of performance parameters have been discussed which fall into the category of economy indicators. In the present work an overview of RMS has been included along with the discussion on comprehensive set of responsiveness and economy indicators for RMS.**

Keywords - Performance indicators, Reconfigurability, Reconfigurable manufacturing system, Reconfigurable machine tool, Machine utilization.

1. INTRODUCTION

The present era belongs to fierce competition and dynamic business environment caused by globalization of economies, fast pace of development in the process technology and the customer driven market. To stay competitive and profitable, the industry has to be responsive to the dramatically changing world in which, emerging economies, new ideas and philosophies of doing business, technical advancements and ever changing needs of customers pose serious challenges to its survival [Hasan et al., 2013; Goyal et al. 2011; Mittal and Jain 2014a; Goyal et al., 2013c; Phanden et al., 2011a, 2011b, 2012a, 2012b, 2013]. To remain in the market, companies must adopt the manufacturing systems that not only produce high-quality products at low cost, but also respond to market changes rapidly in an economical way. The inability of existing/conventional manufacturing systems to cope up with the present manufacturing environment has paved the way for a new class of manufacturing system i.e. reconfigurable manufacturing system (RMS) to respond rapidly and cost-effectively to the ever changing products and process technologies as well as increasingly fluctuating and uncertain demands At the heart of RMS lies the Reconfigurable Machine Tools (RMT) consisting of basic modules (BM) and auxiliary modules (AM) which are capable of performing multiple operations in their existing configurations and can further be reconfigured into more configurations as shown in Figure 1 [Goyal et al., 2012a, 2012d; Hasan et al., 2014b; Sharma et al., 2012]. In such a situation there are many feasible machine configurations available for performing an operation on the part. The RMS behaves as dedicated manufacturing system (DMS) during the production phase and can readily be reconfigured according to the new manufacturing requirements. Therefore like DMS the most appropriate layout for the RMS is also the flow line layout to support mass manufacturing at the competitive cost. In most of the RMS modelling approaches flow line layout has been considered [Hasan et al., 2014a; Mittal and Jain 2014b]. Therefore authors consider the reconfigurable flow line allowing paralleling of similar machines for presenting the performance indicators. The system convertibility has been defined as the capability of a system to adjust production functionality and the system convertibility measures has been presented based on the assessment of convertibility of the system configuration, machines and material handling equipments [Maier-Speredelozzi et al., 2003]. Reconfigurability index has also been proposed based on scalability, modularity, convertibility and diagnosability but the approach does not consider the module changes required at the machine level [Gumasta et al., 2011]. Recently performance measures have been developed to measure the operational capability and machine reconfigurability of reconfigurable machine tools taking into consideration the required module changes [Goyal et al., 2012c; Goyal et al., 2013a].

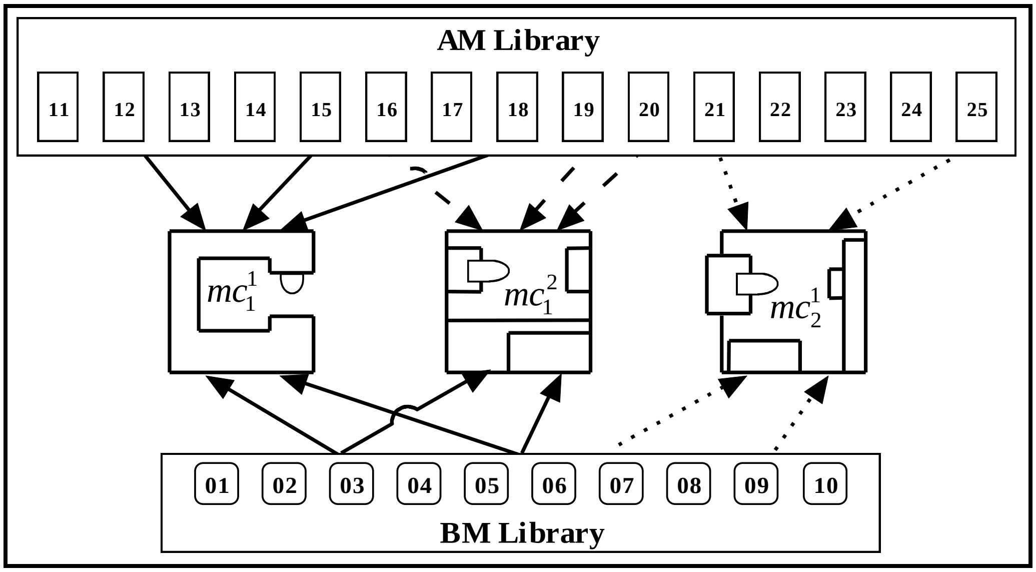

Figure 1. Configuring RMT through module library adapted from Goyal et al., (2012b)

Liles and Huff (1990) have defined an RMS as a system capable of tailoring the configuration of manufacturing system to meet the production demand placed on it dynamically. The concept of 'modular manufacturing' defined by Tsukune *et al.* (1993) is also similar to the Reconfigurable Manufacturing System. Later in 1996 the Engineering Research Centre for Reconfigurable Manufacturing Systems (ERC-RMS) was established at the University of Michigan, Ann Arbor to develop and implement reconfigurable manufacturing systems. Koren *et al.* (1999) defined RMS as:

"*An RMS is designed at the outset for rapid change in its structure, as well as in hardware and software components, in order to quickly adjust the production capacity and functionality within a part family in response to sudden unpredictable market changes as well as introduction of new products or new process technology*".

The most significant feature of the RMS is that the configuration of these systems evolves over a period of time in order to provide the functionality and capacity that is needed, and when it is needed. Reconfigurable Machine Tool (RMT) lies at the heart of reconfigurable manufacturing system, which imparts RMS its distinguishing features i.e. customized functionalities and adjustable capacity through its changeable structure. The reconfigurable machine tools are modular machines comprising of different basic and auxiliary modules [Koren *et al.*, 1999; Moon & Kota, 2002; Goyal et al., 2013b]. The basic modules are structural in nature like base, columns, and slide ways and the auxiliary modules are kinematical or motion providing modules such as spindle heads, tool changers, spacers, indexing units, adapter plates and angle structure, etc. The auxiliary modules are comparatively smaller, lighter and cheaper than the basic modules. Therefore they may be economically and rapidly changed with comparatively lesser effort. The RMTs can be rapidly reconfigured into many other configurations having different functionality and capacity by keeping its base modules and just changing the auxiliary modules. A machine is said to have multiple configurations if it can be converted into other configurations by just changing the auxiliary modules. Figure 1 depicts the configuration of RMTs from the standard module library, in which first and second machine configuration (i.e. mc_1^1 and mc_1^2) of machine one and the first configuration of machine two (i.e. mc_2^1) are configured respectively by assembling the basic modules and auxiliary modules from the module library.

In reconfigurable manufacturing systems an operation can be performed by several feasible alternative machine configurations and over the period demand along with the product mix and functionality changes which requires the change in configuration of the system. Therefore the problem of selecting the machine configurations in RMS is very crucial and needs the elaborative performance measures so as to reduce the reconfigurations required at the later stage. The available literature on RMS reveals two major gaps in the previous research; firstly the near optimal solutions recorded in the first stage taking cost as the only performance measure will lead to losing the overall suitable candidates having high responsiveness with marginally increased costs. Secondly the detailed analysis of module interactions at the machine level has not been considered in most of the RMS models, which is the key enabler of reconfigurability in the RMS. Motivated by these facts, emphasis of the present study is on the development of responsiveness measure at the machine level which would certainly minimize the reconfiguration efforts required at various levels in the later stage.

2. PERFORMANCE MEASURES

In a reconfigurable manufacturing system, the machines are capable of performing variety of operations in its existing configurations and the reconfigurable machine tools (RMT) can further be reconfigured into other configurations. The different configurations thus can further enhance the functionality and can perform number of operations. In such a scenario the availability of large number of machines to perform a single operation, makes it a complex problem to assign the RMTs to the reconfigurable flow lines. Thus to access the suitability of a configuration effectively the performance indicators like machine reconfigurability, operational capability, machine utilization along with the cost are considered in this chapter to optimize the reconfigurable flow lines.

Notations:

mc_i^j machine i ($1< i < I$) in its j^{th} ($1< j < J_i$) configuration

n_i^j number of machines required to satisfy the demand when machine i with j^{th} configuration is selected

D demand rate

FS_k a set of feasible alternative machine configurations to perform k^{th} ($1< k < K$) operation $\{(i_1, j_1), (i_2, j_2),\ldots.(i_f,j_f)\ldots\ldots.(i_{F_k}, j_{F_k})\}$. Here each feasible alternative f ($1< f < F_k$) is defined as (i_f,j_f), where i_f specifies the feasible machine and j_f specifies the feasible machine configuration

CM_i^j cost of machine i with j^{th} configuration (i.e. mc_i^j)

$P_{i,k}^j$ production rate of machine i with j^{th} configuration for performing k^{th} operation

$\delta_{i,k}^j$ 1 if operation k can be performed with machine i having its j^{th} configuration, otherwise 0

$C_{p,q}$ cost of assigning p^{th} machine with q^{th} configuration from the feasible alternative machine configurations to perform an operation at specified demand rate

$MU_{p,q}$ machine utilization of assigning p^{th} machine with q^{th} configuration from the feasible alternative machine configurations to perform an operation at specified demand rate

$CC_{p,q}$ configuration convertibility of assigning p^{th} machine with q^{th} configuration from the feasible alternative machine configurations to perform an operation at specified demand rate

$OC_{p,q}$ operational capability of assigning p^{th} machine with q^{th} configuration from the feasible alternative machine configurations to perform an operation at specified demand rate

$MR_{p,q}$ Machine reconfigurability of assigning p^{th} machine with q^{th} configuration from the feasible alternative machine configurations to perform an operation at specified demand rate

2.1 Performance Parameters to Assess Responsiveness of RMS

The responsiveness at the system level and machine level is primarily governed by the responsiveness offered by the key elements of the system i.e. RMTs. In the following section a novel methodology is developed to measure the responsiveness of the RMTs based on operational capability and machine reconfigurations.

2.1.1 Operational Capability (OC)

The capability of an RMT to readily perform a variety of operations in its existing configuration gives an upper edge to respond to the dynamic behavior of the market and turns into high responsiveness. For performing a particular operation k ($1< k < K$) the operational capability of a feasible alternative machine configuration is computed based upon the variety of operations that can be performed by the machine in its present configuration. As the number of operations that can be performed by a machine increases, its contribution to the operational capability also increases. Our objective is to maximize the operational capability, therefore the operational capability contribution of every additional increase in the operations performed must reflect more pronounced value of operational capability as compared to that of lower values of operational capability. To reflect this consideration a power index Y is used. Deciding the value of Y is a matter of sensitivity analysis which may be carried out to see the overall impact of value of Y on machine selection and its impact on the reconfiguration efforts over the entire planning horizon. The operational capability ($O_{p,q}$) of a feasible alternative machine configurations to perform a particular operation is computed using:

$$OC_{p,q} = \left[\left(\sum_{k=1}^{K} \delta_{p,k}^{q} \right) - 1 \right]^{Y} \tag{1}$$

2.1.2 Machine Reconfigurability (MR)

The quick adaptability of the reconfigurable manufacturing system in response to the dynamic environment is achieved by reconfiguration of the machines. Thus reconfigurability is a criterion to judge the adaptability of the machine configuration. In the present work a novel approach to measure the reconfigurability of an RMT is proposed based on the number of configurations into which an existing machine configuration may be converted along with considering the effort required in conversions in the form of adding/removing and/or readjusting the auxiliary modules. The effort in each configuration conversion is being calculated by a methodology based on set theory. As shown in Figure 2 in each conversion two sets of auxiliary modules are participating one is the set of auxiliary modules of existing machine configuration and the other is the set of auxiliary modules required in the new configuration. Thus the total auxiliary modules i.e. union of the both sets of auxiliary modules is categorized into three classes, the auxiliary modules to be added, removed and readjusted. Here it is assumed that the existing modules which are retained in the next configuration need to be readjusted. Further the ratio of three classes of auxiliary modules to the total modules is multiplied by the weights α, β and γ which gives the effort required in machine configuration conversion. In this way the total effort required for all the possible conversions of existing configuration is calculated. The total reconfiguration effort required is also dependant on the number of copies of the machine configuration required to satisfy the demand rate with the existing configuration, as all the machines are to be reconfigured to change the configuration of existing machine configuration.

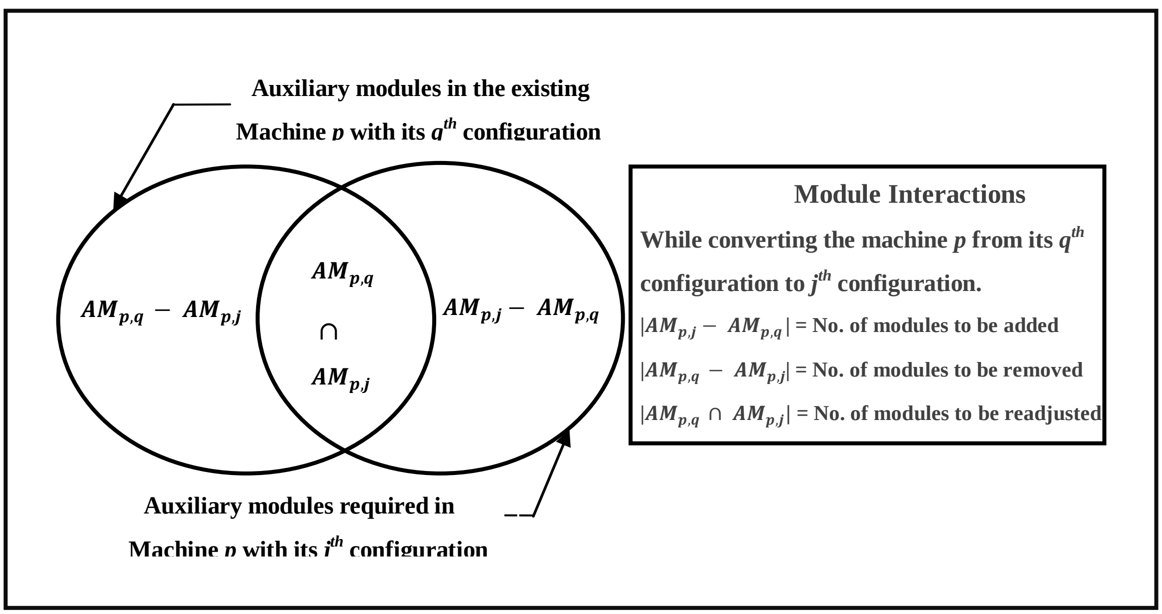

Figure 2. Reconfigurability effort calculation through set theory

For computing the reconfigurability of a machine configuration, the number of configurations into which it can be converted plays a vital role, if a machine is having only one configuration (J_p=1) i.e. it cannot be converted into further any configurations, thus it will not make any contribution in reconfigurability. As the number of configurations into which a machine can be converted increases, its contribution to the reconfigurability also increases. As the objective in general is to maximize the reconfigurability, therefore every additional increase in the number of possible configurations must reflect an increased value of reconfigurability. Therefore the reconfigurability contribution of every additional increase in the J_p must reflect more pronounced value of reconfigurability as compared to that of J_p-1. To reflect this consideration a power index z is used in the Eq. (2). Therefore the reconfigurability ($R_{p,q}$) of a machine configuration is calculated using the following equation.

$$R_{p,q} = [J_p - 1]^Z \Big/ n_p^q \sum_{j=1, j\neq q}^{J_p} \left[\alpha \frac{No.of\ modules\ added}{Total\ modules} + \beta \frac{No.\ of\ modules\ removed}{Total\ modules} + \gamma \frac{No.of\ modules\ readjusted}{Total\ modules} \right]$$

$$= \frac{[J_p - 1]^Z}{n_i^j \sum_{j=1,j\neq q}^{J_p} \left[\alpha \frac{AM_{p,j} - AM_{p,q}}{AM_{p,q} \cup AM_{p,j}} + \beta \frac{AM_{p,q} - AM_{p,j}}{AM_{p,q} \cup AM_{p,j}} + \gamma \frac{AM_{p,q} \cap AM_{p,j}}{AM_{p,q} \cup AM_{p,j}} \right]} \quad (2)$$

Generally α>β>γ ,as the effort required in adding the module is comparatively higher than removing the module and further the effort required in removing the module is reasonably higher than just readjusting the existing modules.

2.1.3 Configuration Convertibility (CC)

Convertibility is defined as the capability of a system to adjust production functionality, or changes from one product to another [Maier-Speredelozzi et al., 2003]. In the present study flow line configuration with crossover connections has been considered. The configuration convertibility is dependent upon the minimum increment of conversion (*I*), the routing connections (*R*) and the minimum number of replicated machines (*X*) [Maier-Speredelozzi et al., 2003]. The preliminary estimation of configuration convertibility ($C_c^{'}$) can be expressed as:

$$C_C^{'} = \frac{R \times X}{I} \quad (3)$$

The equation given below normalizes the value of C_C relative to a pure serial system with the same number of machines and so that the value falls in the range of 1 to 10 for all the system configurations:

$$CC_{p,q} = 1 + \frac{log_{10}\left[\frac{C_c^{'}}{C_{c,Serail}^{'}}\right]}{log_{10}\left[\frac{C_{c,\ K-Parallel}^{'}}{C_{c,\ K-Serial}^{'}}\right] \times \left(\frac{1}{9}\right)} \quad (4)$$

System convertibility includes contributions due to machines, their arrangements or configuration, and material handling devices. These factors are mapped together for an overall assessment of system convertibility.

2.2 Performance Parameters to Assess Economy of RMS

2.2.1 Cost (C)

Cost is the important performance parameter driving the selection of machine configuration for a particular operation. Thus meeting the customer demands economically is most important. The cost ($C_{p,q}$) of a feasible alternative machine configuration for performing k^{th} operation at specified demand rate is calculated using:

$$C_{p,q} = n_p^q \times CM_p^q \quad (5)$$

where $$n_p^q = \left\lceil \frac{D}{P_{p,k}^q} \right\rceil \quad (6)$$

2.2.2 Machine Utilization (MU)

In the present scenario industries are facing a stiff global competition and volatile markets. In such circumstances utilization of the manufacturing system capacity is very crucial for sustenance and growth of the concern and underutilization of machine capacity which in turn affects the economic functioning may pose a serious threat to the survival of industry. Therefore the system should be utilized to the maximum possible extent by optimizing the system configuration. In the reconfigurable manufacturing environment the availability of multifunctional machines which can further be reconfigured into various configurations turns the machine selection problem into combinatorial problem. Therefore, while selecting the system configuration for a part the machine utilization should be given due consideration.

$$MU_{p,q} = \frac{D}{P_{p,k}^q \times n_p^q} \quad (7)$$

The challenges of the present manufacturing environment have given birth to a new objective Manufacturing Responsiveness. It appraises the ability of a manufacturing system to respond to disturbances which impact upon production goals and consequently, its ability to adapt to changing market conditions [11]. This in turn necessitates redesign and replanning of manufacturing systems more frequently and within shorter lead time to reconfigure them to fulfil the changed production requirements. In reconfigurable manufacturing systems the reconfigurability had been the key issue which in general can be defined as the ability of a system to repeatedly change and reorient its components easily and cost effectively to achieve the variety of objectives. The reconfigurability at machine level can be achieved by changing the functionality and capacity through adding/removing or readjusting the existing auxiliary modules. In general the RMTs are capable of performing variety of operations in each of its existing configuration, which may be treated by considering the operation capability and the configurations into which an RMT can further be reconfigured by changing its auxiliary modules adds to its reconfigurability. Both the operation capability and the reconfigurability depict the responsiveness of the RMTs which further governs the responsiveness of the reconfigurable manufacturing system.

3. CONCLUSION AND FUTURE SCOPE

In the present study performance measures for measuring the responsiveness of the Reconfigurable Manufacturing System based on machine reconfigurability and operational capability and convertibility has been discussed. The performance measure discussed would help the management to enhance the decision quality in the reconfigurable manufacturing system by providing an apparent tradeoff between economy and responsiveness. This is very much apparent that the application of proposed responsiveness measures will lead to reduction in the reconfiguration efforts for the multiple period configurations planning in the RMS. In future authors plan to apply the developed indices to the manufacturing lines with multiple demand scenarios along with multi part manufacturing flow lines.

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