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Machine Reconfigurability Models Using Multi-Attribute Utility Theory and Power Function Approximation

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Abstract

Reconfigurable Machines (RMs) are considered to be one the key elements of modern manufacturing systems like Reconfigurable Manufacturing Systems (RMSs). These machines offered customized flexibility in terms of capacity and functionality. These machines are modular machines assembled using basic/essential modules and auxiliary modules. These RMs can be reconfigured into several other configurations offering variable functionality and capacity by keeping its base modules and just adding/removing or adjusting the auxiliary modules. Measuring machine reconfigurability may be considered as one of the important parameter in assessing the performance of these manufacturing systems. In the present paper, reconfigurability models were developed using Multi Attribute Utility Theory (MAUT) and Power Function Approximation. The developed models are explained and demonstrated using multi stage serial reconfigurable product flow line.

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Keywords: Machine reconfigurability; RMS; multi attribute utility theory; power function approximation

1. Introduction

Reconfigurable Manufacturing Systems (RMSs) are considered to be new generation of manufacturing systems well equipped to provide the desired functionality and capacity as and when needed. The Reconfigurable Machine Tool (RMT) or Reconfigurable Machines (RMs) plays a key role in the contentment of this objective because of

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their modular structure. The structure of these machines comprised of basic/essential modules and auxiliary modules along with the open architecture software (Fig.1).

Fig.1 RMT configurations using essential/basic and auxiliary modules.

These reconfigurable machines are considered to be the core component of any RMS as they provide RMS its distinctive characteristics of customized functionalities and capacity through a reconfigurable structure. The primary idea behind reconfigurable machines was initiated by Koren et al. (1999) and later some useful contributions in the development of these machines were made by Landers (2000) and Moon and Kota (2002). The building blocks of these modular machines are categorized as basic/essential modules and auxiliary modules. The basic/essential modules are generally structural in nature such as base, columns, and slide ways, whereas auxiliary modules are mostly kinematic or motion-providing modules which include 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, so they may be economically and quickly changed with less effort. An RMT is assembled by combining basic modules and auxiliary modules depending upon the desired requirements. In the paper both the terms RMTs and machines are synonymous. According to Goyal et al. (2012) RMTs can be reconfigured into many other configurations which may offer flexible functionality and capacity by keeping its base modules and just adding/removing or adjusting 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. In general, reconfigurability is defined as the ability to add, remove and/or rearrange in a timely and cost-effective manner the components and functions of a system, which can result in a desired set of alternate configurations (Farid and McFarlane, 2007). The same definition can be used to define the reconfigurability associated with reconfigurable machines as, the effort required in converting one existing machine configuration to another under some constraints and with some desired objectives. Defining reconfigurability of reconfigurable machines in the form of some mathematical parameter or index is still a very wide open issue for research. Gumasta et al. (2011) defined reconfigurability as an engineering characteristic related to the design of production machines and manufacturing systems capable of producing customized products in the cost effective manner. The reasons for the lack of quantifiable indices for reconfigurability might be because of the fact that factors contributing towards reconfigurability are numerous due to which it becomes extremely difficult in finding the functional relationship among these variables. Nevertheless, in literature some authors have proposed certain mathematical relations for reconfigurability based on some identified factors contributing towards machine reconfigurability. One of the reasonably useful relationships between machine reconfigurability and machine modules is proposed by Goyal et al. (2012). The developed machine reconfigurability model is based on fundamental set theory. The work on developing machine reconfigurability has been very limited and most of the research done deals with the reconfigurability of the RMS system as a whole. The overall aspect of reconfigurability can be better quantified once some indices for machine and other sub-system reconfigurability can be formulated.
In this paper, assessment of machine reconfigurability is done by formulating mathematical models using multi-attribute utility theory and power function approximation. While employing multi-attribute utility theory, the machine reconfigurability parameter is mapped to the various machine attributes contributing towards reconfigurability. While the power function approximation model is simply based on direct and inverse proportionality relationships of the attributes contributing towards reconfigurability of machines. The developed models are explained in the following sections with the help of a multi-stage serial reconfigurable product flow line.

**Nomenclature**

| Symbol | Definition |
|--------|------------|
| $j_i^{MA}$ | number of auxiliary modules added while converting $i^{th}$ machine configuration to $j^{th}$ configuration |
| $j_i^{MR}$ | number of auxiliary modules removed while converting $i^{th}$ machine configuration to $j^{th}$ configuration |
| $j_i^{MD}$ | number of auxiliary modules readjusted while converting $i^{th}$ machine configuration to $j^{th}$ configuration |
| $\alpha$ | weight associated with the addition of modules as required by the new machine configuration |
| $\beta$ | weight associated with the removal of unwanted modules of existing machine configuration while changing over to the new configuration |
| $\gamma$ | weight associated with the readjustment of modules which are common both in existing and new configurations |
| $j_i^{E}$ | effort required while changing $i^{th}$ machine configuration to $j^{th}$ |
| $N_i$ | number of individual machines required on each stage on the product flow line to fulfil the desired demand |
| $p_{i,k}^{j}$ | production capacity of $i^{th}$ machine in its $j^{th}$ configuration performing $k^{th}$ operation |
| $Q_{i}^{j}$ | number of operations which can be performed by $i^{th}$ machine in its $j^{th}$ configuration |
| $Q_i$ | number of configuration in which $i^{th}$ machine can be reconfigured |
| $w_E$ | weight associated with effort required to reconfigure a machine |
| $w_O$ | weight associated with the number of operations performed by a machine |
| $w_q$ | weight associated with number of configurations in which $i^{th}$ machine can be reconfigured |
| $\varphi_1$ | power index for term $(Q_i - 1)$ |
| $\varphi_2$ | power index for term $(O_{i}^{j} - 1)$ |
| $R_{i}^{j}$ | Reconfigurability of $i^{th}$ machine in its $j^{th}$ configuration |

2. Literature Review

The modern manufacturing systems like RMSs and Hybrid systems are struggling with the issue of how to measure and quantify reconfigurability parameter. Farid et al. (2008) coined the term “reconfiguration ease” which may be taken as a qualitatively measure of reconfigurability which largely depend on the system’s modularity. According to Maier-Speredelozzi (2003) the term reconfigurability is synonymous with convertibility. In the work Maier-Speredelozzi (2003) quantified convertibility of manufacturing system based on metrics so that the performance of different manufacturing systems can be compared with respect to reconfigurability or convertibility. These metrics so developed are based on assessments of the configuration itself, and the system level components such as machines and material handling devices. The methodology developed by Maier-Speredelozzi (2003) is useful for quantifying convertibility and comparing system configurations during the early phases of design, without requiring detailed product or process plan information. The work carried out by Maier-Speredelozzi (2003) takes into account the overall reconfigurability measure of the system as a whole with limited focus on reconfigurability associated with machines. Gumasta et al. (2011) developed an index to measure the overall reconfigurability of RMSs by taking into consideration various core characteristics such as modularity, scalability, convertibility and diagnosability associated with these systems. These characteristics have been mapped together using multi-attribute utility theory. According to Gumasta et al. (2011) the developed index is a tool which could help the manufacturer in deciding to extend to which a particular manufacturing system is
reconfigurable. As the developed index is based on the core characteristics of reconfigurability, it helps in understanding the various aspects of reconfigurability. Also, it enables to directly link reconfigurability to the fundamental parameters of the manufacturing system. The findings of the study by Gumasta et al. (2011) are useful in the process of decision making for deciding which parameter needs more attention for increasing the reconfigurability of the RMS. Although, there is no mention of how reconfigurability associated with RMTs can be evaluated. Goyal et al. (2012) carried our comprehensive work on performance measures associated with reconfigurable manufacturing systems. In the work, various indices for cost, operational capability and reconfigurability were developed. The index developed for machine reconfigurability is based on the effort required to covert a machine from one configuration to another. It also takes into account some other parameters like demand, and machine capacities as well. In this paper, the methodology adapted for developing the reconfigurability models is explained in the following sections.

3. Methodology

3.1. Machine Reconfigurability

For a reconfigurable machine there are numerous variables or attributes which may contribute towards its reconfigurability. These variables or attributes may contribute either in a positive or negative way towards the reconfigurability. The study by Goyal et al. (2012) gives a basic idea of how machine configurability can be evaluated under certain demand condition for a given product flow line. The following attributes are the most common factor which can affect the reconfigurability of any machine.

- The number of configurations into which an existing machine configuration can be converted.
- The effort required for each of the above conversion in the form of adding/removing and/or readjusting the auxiliary modules.
- Operational capability of machines i.e. the number of distinct operations which a machine is capable of performing.
- Production capacity of the machines, and
- The product demand which in turn determines the required number of machines for each stage on the product flow line.

The effort for converting an existing machine configuration to a new configuration can be computed by applying simple set theory principles (Goyal et al., 2012). An existing machine configuration can be converted into a new machine configuration by adding the auxiliary modules required by the new machine configuration, removing the unwanted auxiliary modules which belong to the existing machine configuration and readjusting the modules which are common for both existing and new configuration. In general, the degree of effort required in adding is more than the effort required in removing and is more than the effort required readjusting these modules. This aspect of effort can be incorporated by defining weights $\alpha$, $\beta$ and $\gamma$, where $\alpha < \beta < \gamma$. Mathematically, effort required in changing $i^{th}$ machine configuration to $j^{th}$ configuration can be computed as

$$
E_i^j = \sum_{k=1}^{N} \left( \alpha \frac{\text{No. of Modules added}}{\text{Total Modules}} + \beta \frac{\text{No. of Modules removed}}{\text{Total Modules}} + \gamma \frac{\text{No. of Modules readjusted}}{\text{Total Modules}} \right)
$$

(1)

$$
= \sum_{k=1}^{N} \left( \frac{\alpha \text{MA}_i^j + \beta \text{MR}_i^j + \gamma \text{MD}_i^j}{\text{MA}_i^j + \text{MR}_i^j + \text{MD}_i^j} \right) \quad \text{where} \ \alpha+\beta+\gamma=1
$$

(2)

On the basis of conversion effort $(E_i^j)$, a machine configuration is said to have higher configurability values if less effort required in converting this machine configuration to any other configuration, e.g. machine configuration $mc_1^1$ should have higher reconfigurability as compared to machine configuration $mc_1^2$ as the effort required to convert machine configuration $mc_1^1$ to other configuration is higher (1.3) as compared to the effort required to convert machine configuration $mc_1^2$ to other possible configuration (0.68). On the basis of operational capability
A machine configuration is said to have higher reconfigurability value if it can perform higher number of operations as compared to any other machine configuration. For example, comparing machine configurations \(mc_1^1\) and \(mc_2^1\), the reconfigurability value of configuration \(mc_2^1\) should be higher as compared to machine configuration \(mc_1^1\) as \(mc_2^1\) is capable of performing 4 operations as compared to 3. Further, a machine is said to have higher reconfigurability values if it can be converted more number of configurations as compared to any other machine. For example, machine configuration \(mc_1^1\) is supposed to have higher reconfigurability value as compared to machine configuration \(mc_1^2\) as machine \(mc_1^1\) can be converted to 3 more configuration as compared to 2 more configuration for machine \(mc_1^2\). For a particular demand to be fulfilled by a product flow line, a machine configuration is said to have higher if there are more number of machines for a particular operation as compared to any other machine configuration, e.g. for a demand of 300 units, for the product flow line shown in Fig. 2, for operation 10, selecting machine configuration \(mc_2^1\) (Machine capacity = 10 parts/hr for operation-10) requires 30 number of machines (300/10). While selecting machine \(mc_2^3\) for the same operation with capacity 30 parts/hr would require 10 numbers of machines (300/30). Meaning thereby, the reconfigurability of machine \(mc_2^1\) should be higher as compared to machine configuration \(mc_2^3\).

The objective here is to develop some mathematical models or relations which can quantify the combined effect of all the above discussed variables or attributes affecting the reconfigurability of a machine. The following two types of model were proposed based on (1) multi attribute utility theory, and (2) power function approximation for calculating the reconfigurability values associated with machines in a Reconfigurable Manufacturing System.

3.2. Model based on Multi Attribute Utility Theory

Huber (1974) introduced multi attribute utility theory for overall evaluation of any characteristic \(\xi(x)\) of an object ‘x’. It is defined as a weighted sum of its evaluation with respect to its relevant variables affecting the desired characteristic. The overall evaluation is defined by the following value function

\[
\xi(x) = \sum_{i=1}^{n} w_i \cdot v(x), \quad \text{where} \quad \sum_{i=1}^{n} w_i = 1
\]

Here, \(\xi\) is the evaluation of the object ‘x’ on \(v^{th}\) dimension and \(w\) is the weight determining the impact of \(v^{th}\) variable on the overall evaluation and \(n\) are the number of variables affecting the required characteristic.

It can be easily realized that for any reconfigurability model for RMS, the variables or attributes contributing towards its measure can be divided into two categories, one associated with the machine and the other associated with the product flow line configuration. The variables associated with the machines are the effort and the operational capability while on the other hand variables associated with the flow line configuration are the demand and production capacity of the machines which in turn determines the number of machines required to fulfill that demand. For any product flow line configuration, number of machines required to fulfill the required demand can be calculated as

\[
N_i = \frac{D}{P_{i,k}}
\]

For example, for the product flow line as shown in Fig.2, say, if machine configuration \(mc_2^1\) is selected at stage-1 for performing operation-10, then for a demand of say 300 with machine capacity of 30 parts/hour, the required number of machines is 300/30=10machines.

In order to evaluate reconfigurability, variables namely effort, number of machines (calculated using the required demand and production capacity of the selected machine) and operational capability have been mapped together and the following model is developed for assessing machine configurability.
Weights for individual attributes i.e. \( w_E, w_q \) and \( w_Q \) can be calculated from on the basis of relative importance which the manufacturer assigns to these attributes contributing towards reconfigurability. Though, in this paper these values are arbitrary assumed.

### 3.3. Power Function Approximation

The power function is of the basic form \( \Phi(x) = ax^b \). The parameter ‘a’ serves as a simple scaling factor and the parameter ‘b’, called either the exponent or the power, determines the function’s rates of growth or decay. Depending on whether it is positive or negative, a whole number or a fraction, \( b \) determines the function’s overall shape and behavior.

It is justifiable to state that the reconfigurability of any machine configuration should hold a direct proportionality relationship with variable \( Q_i \). Further, an inverse proportional relation is valid for the effort, \( E_{ij} \) required for converting one machine configuration to another. Also, a direct relationship holds between machine reconfigurability and its corresponding operational capability. The above relationships can be transformed in the following mathematical form

\[
R_i^j = \begin{cases} 
0; & \text{for } Q_i, O_i^j = 1 \\
\frac{1}{w_E} \left( \frac{1}{E_{ij} \ast \left( \frac{D}{P_{ik}} \text{ or } N_i \right)} \right) + w_O (O_i^j - 1) + w_q (Q_i - 1); & \text{for } Q_i > 1, O_i^j > 1; \text{where, } w_E + w_O + w_Q = 1 
\end{cases}
\] (5)

The proportionality relationship can be transformed into an equality relationship by simply introducing a constant term. The constant term also helps in normalizing the values of reconfigurability so that the obtained value lies in the range 0 to 1. Thus, the above equation can be written as

\[
R_i^j = \frac{(Q_i - 1)^b (O_i^j - 1)^{b_2}}{E_{ij} \ast \left( \frac{D}{P_{ik}} \text{ or } N_i \right)}
\] (6)

For any RMT, number of configurations and its operational capability plays a more dominant role in determining its reconfigurability in comparison to any other machine or flow line attribute. If a machine has only one configuration (i.e. \( Q_i = 1 \)), it cannot be converted into any further configurations, meaning thereby that the reconfigurability of any such machine is zero. Similar is the case with the operation capability of the machine.
Hence, to have a more pronounced effect of the both these attributes, the power terms $\varphi_1$ and $\varphi_2$ are used in the above developed relationship (equations 6 & 7).

The indices developed are illustrated using the following example.

4. An Illustrative Example

Consider a multi stage serial reconfigurable product flow line as shown in Fig. 2. The machines selected for the desired operations are shown with a colored block. The structural characteristics and the operational capabilities along with the capacity are shown in tables 1 and 2 respectively.

Fig 2. A reconfigurable serial multi stage product flow line.
Table 1: Structural features of the machines along with the effort values

| Machine | Configuration | Basic Module | Auxiliary Module | Effort |
|---------|---------------|--------------|------------------|--------|
| M₁      | mc₁¹           | {D, E, G}    | {e, g, h, k}     | 1.13   |
|         | mc₂¹           | {D, E, G}    | {f, h, m, p, z}  | 1.30   |
|         | mc₃¹           | {D, E, G}    | {a, g, d, j, k}  | 1.09   |
|         | mc₄¹           | {D, E, G}    | {b, s, g, d, k}  | 1.11   |
|         | mc₁²           | {F, I}       | {a, d, s, c}     | 0.68   |
| M₂      | mc₂²           | {F, I}       | {a, d, v, c, z}  | 0.61   |
|         | mc₂³           | {F, I}       | {g, s, v, z}     | 0.76   |
|         | mc₃³           | {A, X, Z}    | {a, d, g, r, t, v} | 0.35   |
| M₃      | mc₂²           | {A, X, Z}    | {a, w, d, c}     | 0.38   |
|         | mc₃¹           | {G, M, Q, R} | {a, f, g, k, m}  | 1.33   |
|         | mc₃²           | {G, M, Q, R} | {a, d, p, m, x}  | 1.45   |
| M₄      | mc₃³           | {G, M, Q, R} | {f, s, t, k, p}  | 1.51   |
|         | mc₃⁴           | {G, M, Q, R} | {f, d, m, g}     | 1.38   |
|         | mc₃⁵           | {G, M, Q, R} | {g, s, p, m}     | 1.41   |
| M₅      | mc₁⁵           | {B, W, Z}    | {f, s, p, v, u, z} | 0.76   |

Table 2: Operational capability of machine configurations.

| Machine Config. | Operation |
|-----------------|-----------|
| Config.         | 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 |
| mc₁₄            | 10 - - - 20 - - 25 - - - - - - - - |
| mc₂₄            | - - 30 - - - - 15 - - - - 20 - - 30 - - - - - - |
| mc₃₄            | - 10 - - - - - - - - - - - - - - - - |
| mc₄₄            | 20 - - - - - - - - - - - - - - - - - |
| mc₅₄            | - - 25 - - - - - - - - - - - - - - |
| mc₁₅            | - - - 35 - - - - - - - - - - - - - |
| mc₂₅            | 15 - - - - - - - - - - - - - - - - |
| mc₃₅            | - - - - 10 - - - - - - - - - - - |
| mc₄₅            | - 20 - - - - - - - - - - - - - - |
| mc₅₅            | - - - - - - - - - - - - - - - - |
| mc₁₆            | 15 - - - - - - - - - - - - - - - - |
| mc₂₆            | - - - - - - - - - - - - - - - - |
| mc₃₆            | - - - - - - - - - - - - - - - - |
| mc₄₆            | - - - - - - - - - - - - - - - - |
| mc₅₆            | - - - - - - - - - - - - - - - - |
| mc₁₇            | 10 - - - - - - - - - - - - - - - - |
| mc₂₇            | - - - - - - - - - - - - - - - - |
| mc₃₇            | - - - - - - - - - - - - - - - - |
| mc₄₇            | - - - - - - - - - - - - - - - - |
| mc₅₇            | - - - - - - - - - - - - - - - - |
| mc₁₈            | - - - - - - - - - - - - - - - - |


For calculating the reconfigurability measure the following values are used:

Demand = 300 units

\( \alpha = 0.5; \beta = 0.4; \gamma = 0.1 \)

\( w_Q = 0.5; w_0 = 0.3; w_6 = 0.2 \)

\( \phi_4 = 3 \text{ and } \phi_2 = 2 \)

The reconfigurability values of the machines for the serial reconfigurable product flow line are computed using the above developed models and are presented in Table 2.

| Machine Configuration | Using Multi Attribute Utility Theory | Using Power Function Approximation |
|-----------------------|-------------------------------------|----------------------------------|
| \( mc_1 \)           | 2.412                               | 0.264                            |
| \( mc_2 \)           | 2.718                               | 0.924                            |
| \( mc_3 \)           | 2.412                               | 0.269                            |
| \( mc_4 \)           | 1.633                               | 0.023                            |
| \( mc_5 \)           | 1.922                               | 0.061                            |
| \( mc_6 \)           | 1.909                               | 0.025                            |
| \( mc_7 \)           | 1.448                               | 0.000                            |
| \( mc_8 \)           | 1.444                               | 0.000                            |
| \( mc_9 \)           | 2.607                               | 0.130                            |
| \( mc_{10} \)        | 2.913                               | 1.000                            |
| \( mc_{11} \)        | 2.605                               | 0.091                            |
| \( mc_{12} \)        | 2.314                               | 0.000                            |
| \( mc_{13} \)        | 1.622                               | 0.015                            |
| \( mc_{14} \)        | 1.624                               | 0.017                            |
| \( mc_{15} \)        | -                                   | -                                |

*Normalized using maximum value of reconfigurability obtained i.e. 2.913 so that the values lie between 0 to 1.

5. Discussion and scope for future work

The developed models provided an insight of how the reconfigurability of modular machines can be assessed. For the given production flow line with a demand of 300 units, maximum reconfigurability comes out to be for machine \( mc_5 \) using both the approaches. Reconfigurability values of all the machines are relative to this machine for which highest value is obtained in the given production scenario. The trend obtained using both the models is the same but due to power terms used in power function approximation model the reconfigurability values comes out to be on the lower side. The developed models along with some optimization techniques can be used to determine optimum selection of machine configurations for any product line with the objective of selecting those machine configurations which can offer highest reconfigurability values. Higher reconfigurability value simply means that there exist high chances that this machine is capable to changing its configuration to some other configuration as per the requirement. In future, more comprehensive models can be developed which can take care of other features associated with the machines like tool changer, material handling devices, machine envelop etc. Also, reconfigurability models can be further developed for the flow lines having multiple part families.
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