Synthesis of Evolving Cells for Reconfigurable Manufacturing Systems

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Abstract. The concept of Reconfigurable Manufacturing Systems (RMSs) was formulated due to the global necessity for production systems that are able to economically evolve according to changes in markets and products. Technologies and design methods are under development to enable RMSs to exhibit transformable system layouts, reconfigurable processes, cells and machines. Existing factory design methods and software have not yet advanced to include reconfigurable manufacturing concepts. This paper presents the underlying group technology framework for the design of manufacturing cells that are able to evolve according to a changing product mix by mechanisms of reconfiguration. The framework is based on a Norton-Bass forecast and time variant BOM models. An adaptation of legacy group technology methods is presented for the synthesis of evolving cells and two optimization problems are presented within this context.

Keywords: Reconfigurable Manufacturing Systems, Manufacturing System Design, Group Technology, Cellular Manufacturing Systems.

1. Introduction

The concept of Reconfigurable Manufacturing was first proposed by researchers at the University of Michigan in the late 1990s. A definition of Reconfigurable Manufacturing Systems was presented by Koren et al [1]: “A Reconfigurable Manufacturing System (RMS) is designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements.”

The RMS concept has evolved out of the global manufacturing challenges of: economically managing the rapid rate of product development, frequent changes in parts and products, fluctuations in product demand and mix and changes in product and process technology [2]. In order to address these challenges RMSs are envisioned to exhibit transformable system layouts, reconfigurable processes, cells and machines. International research is currently being conducted in order to develop a new set of operating principles and methods for RMSs to be able to exhibit these characteristics; this research included the development of new group technology and factory floor design methods.
This paper presents a group technology framework for the development of evolving manufacturing cells that will enable RMSs to effectively deal with changes in products and the rapid development of new products. The paper proceeds as follows: section two presents relevant literature on recent developments in RMS design; section three develops the RMS cell design problem using a Norton-Bass forecast and BOM Models; section four presents the concept of evolving manufacturing cells and an adaptation of existing group technology methods for their design; section five presents two optimization problems within the scope of evolving cells and section six concludes with a discussion of future work.

2 Relevant Literature

A method for the design of a RMS was presented by Koren and Shpitalni [3]. The method extends to the design of a RMS line for a single part family. The method focused on generating feasible line configurations for the manufacturing of the part family and selection of the best configuration by means of throughput, investment cost, reconfigurability and scalability analysis. The use of the Analytic Hierarchy Process, (AHP), was proposed by Abidi [4] as an advanced decision making tool for the selection of the best configuration (machine placement) in a RMS line. The AHP required a set of RMS design alternatives and a set of design criteria as inputs to the algorithm. Abdi listed reconfigurability, cost, quality and reliability as the design objectives. The use of a Genetic Algorithm to design a Multiple Part Line (MPL) for RMSs was proposed by Tang et al [5]. Tang et al defined a MPL as a line that consists of several serial stages with a finite size buffer between every two stages. The objective of the optimisation was to allocate machines to the various stages of the MPL from a given library of available machines thereby optimizing the line configuration.

Galan et al [6] proposed a group technology method for part family formation for a RMS. The methodology starts by similarity analysis between pairs of products. The method then makes use of the AHP methodology and the Average Linkage Clustering algorithm in order to develop a dendogram that shows the diverse sets of product families that may be formed. The final selection of part families is then left to the discretion of the designer.

The literature has revealed that much of the RMS design methodologies being developed focused on the physical placement (configuration) of machines in a manufacturing line or cell. Little development was found on new group technology methods for RMS. Existing literature focused on the development of static machine-part groups for RMS. This paper proposes the concept of evolving machine-part groups for manufacturing cells that are able to respond more efficiently to changes in the part mix as dictated by the master production schedule.

3. Formulation of the Evolving Cell Problem

3.1 Long Term Forecasting and the Norton-Bass Model
A reconfigurable manufacturing system by definition is a system that is designed for a rapid change in structure as well as in hardware and software components. A RMS cannot change its structure rapidly and cost effectively unless the system design facilitates a transition from an existing configuration to new configuration. Pre-emptive knowledge is necessary such that the current manufacturing system configuration (physical design) can easily transition to a new configuration. A RMS can therefore be defined, from a design perspective, as a system whose current structural state supports a quick and seamless transition to a new structural state.
The Norton-Bass model is one such model that can provide pre-emptive information on how a RMS should evolve over time in order to meet market demand. The Bass Model was originally introduced by Frank Bass [7] to forecast the performance of a new product in the market place. The Bass model is noted as being one of the most widely used, frequently referenced and thoroughly researched marketing models in the world. The model was extended by Norton and Bass [8] to include the modelling of market performance for multiple generations of products. Significant information that may be derived from the Norton-Bass model includes timing for market launch of new products, rates of sales increase/decline, time of peak sales and the market growth and interplay of successive product generations.

The Norton-Bass model for four successive generations of a single product is given by:

\[ S_i(t) = F(t) m_i [1 - F(t - \tau_2)], \]  
\[ S_2(t) = F(t - \tau_2) [m_2 + F(t)m_4] [1 - F(t - \tau_3)], \]  
\[ S_3(t) = F(t - \tau_3) [m_3 + F(t - \tau_2) [m_2 + F(t)m_4]] [1 - F(t - \tau_4)], \]  
\[ S_4(t) = F(t - \tau_4) [m_4 + F(t - \tau_3) [m_3 + F(t - \tau_2) [m_2 + F(t)m_4]]] \]  

Where \( S_i(t) \) is the total sales at time \( t \), \( m_i \) is the incremental market potential and \( \tau_i \) is the time to market of the \( i \)th generation. The cumulative probability density of product adoption is given by:

\[ F(\cdot) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \]  

Where \( p \) is the innovation coefficient and \( q \) is the imitation coefficient. A full discussion of the Norton-Bass model and the estimation of its parameters are beyond the scope of this paper, however equations (1)-(4) provide the information required to determine the product mix and volume at a given time. This will ultimately determine how the manufacturing cells should evolve over a period of time. Figure 1 shows a typical Norton-Bass model forecast for two products with two generations. The dashed lines indicate the times in the lifecycle of the manufacturing system where the part mix can be expected to change.

3.2 BOM Models and Property Maps

The design of a manufacturing system and investment in capital equipment is an investment that will influence its profitability and productivity over a long period of time. In order to pre-empt the changing part mix in a RMS, over a long period of time, the results of the Norton-Bass model must be coupled with a time varying Bill of Materials (BOM) trees as shown in Figure 2. A BOM Tree must be available for each curve that is shown on the Norton-Bass Model. Each product to be manufactured in the RMS over the design life cycle must be modelled by a BOM Tree as shown. Each BOM Tree consists of entities \( E_i \) (vertices), where an entity represents either a part or a subassembly that is required for complete manufacturing of the product. With respect to product structure, each entity \( E_i \) with an in-edge is a parent entity to the entity \( E_j \) with the corresponding out-edge. This use of vertices and directed edges models a part to assembly/subassembly relationship. Property maps are the main link...
between the abstract nature of the BOM Tree and additional characteristics of product variety and manufacturing requirements.

\[
\text{Variety Property Map}
\]
Considering that variety will exist within a product, an entity \( E_j \), may be binary selective for integration into parent \( E_i \), i.e. \( N_{ij} \in \{0,1\} \). The entity may also be selected for integration into the parent in different quantities according to the variety that is required, i.e. \( n_{\min} \leq N_{ij} \leq n_{\max}, N_{ij} \in \mathbb{Z}^+ \). In order to forecast the demand of an entity \( E_j \) over the design lifecycle of the manufacturing system, a probability distribution function \( P_{ij} \) is introduced over the range \([n_{\min}, n_{\max}]\). Every parent entity \( E_i \) will therefore contain a Variety Property \( (V_i) \) of constituent entities \( E_j \) coupled with a probability distribution that describes the likelihood and quantities of \( E_j \) being instantiated in \( E_i \), i.e. \( V_i = \{(E_j, P_{ij})\} \).

\[
\text{Make or Buy decisions and Manufacturing Resource Map}
\]
Not every entity in the BOM tree will be manufactured in a RMS; some entities may be bought or the manufacturing may be outsourced. It is therefore essential to attach a Make or Buy property \( (MB_i) \) to each entity of the BOM tree in order to determine manufacturing system design requirements from this tree, \( MB_i \in \{\text{Make, Buy}\} \). In addition to the make or buy property, a manufacturing resource property is required for each entity \( E_i \). For those entities that have property \( MB_i = \text{Make} \), an ordered list of machines \( M_i = \{m_1, m_2, ..., m_n\} \) is attached to the node \( E_i \), this is the manufacturing resource property. The list is ordered to represent the sequence of machine visitation such that \( E_i \) can be manufactured with the correct operation precedence. For those machines that have property \( B_i = \text{Buy} \), \( M_i = \emptyset \).

\[
\text{Time Varying Machine-Part Matrix and Product Demand}
\]
The output of propagating the results of the Norton-Bass model through each BOM Tree associated with a forecast curve will yield a unique machine-part matrix for various time periods in the lifecycle of a RMS. It will also yield a time varying demand characteristic for each entity \( E_i \). It is essential that this information be available at the outset of the RMS cell design such the the evolution of the machine-part group associated with the reconfigurable cell can be optimized over a long term horizon.

4. Development of Evolving Manufacturing Cells

An evolving manufacturing cell is one in which the capacity of the cell changes, as well as the machine-part grouping. This section addresses the issue of formulating evolving machine-part groups. The primary objective of the cellular manufacturing paradigm is to reduce material flow complexity in the manufacturing system. The objective of system design for reconfigurable manufacturing is to provide the exact manufacturing functionality and capacity where it is needed, when it is needed. In order to achieve this, a slight variation applied to legacy cell formation methods. These are the steps:

1. a unique machine-part matrix is formulated for various time periods,
2. Legacy algorithms are applied to block diagonalize the matrix. Methods used may include PFA [9], Rank Order Cluster Algorithm[10], etc. 
3. The block diagonals in each matrix are paired using a similarity coefficient to propose evolving groups; 
4. Machine migrations from one group to another are identified and are submitted for a two stage filtration process (Discussed in Section 5)

Proposal of Evolving Machine-Part Groups- Illustration by Example 
Consider the two machine-part matrices shown in Figure 3. These matrices correspond to the parts that are to be manufactured by a RMS in two different time periods or reconfiguration cycles:

| Time Period One | Time Period Two |
|-----------------|-----------------|
| M1 | D | E | F | G | H | I |
| M1 | X | X | X | X | X | X |
| M2 | X | X | X | X | X | X |
| M3 | X | X | X | X | X | X |
| M4 | X | X | X | X | X | X |
| M5 | X | X | X | X | X | X |
| M6 | X | X | X | X | X | X |
| M7 | X | X | X | X | X | X |
| M8 | X | X | X | X | X | X |

Figure 3: Machine – Part Mix in RMS for Two Different Time Periods

If the parts and machines from these two time periods are combined into a single matrix as in legacy methods and groups are formed, the resulting groups are as shown in Figure 4. The resulting machine-part groups may be considered static as they prevail over the lifecycle of the associated manufacturing cells. The final solution contains three intra-cell movements as shown by the off-diagonal elements.

| A | B | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|---|
| M1 | X | X | X | X | X | X | | |
| M2 | X | X | X | X | X | X | | |
| M3 | X | X | X | X | X | X | | |
| M4 | X | X | X | X | X | X | | |
| M5 | X | X | X | X | X | X | | |
| M6 | X | X | X | X | X | X | | |
| M7 | X | X | X | X | X | X | | |
| M8 | X | X | X | X | X | X | | |

Figure 4: Group Formation by Merging Part Mix

When the two smaller matrices are diagonalized independently per time period the results are as shown in Figure 5. Evolving cellular groupings are identified by pairing the block diagonals in the two different matrices using the Jaccard similarity index:
The index is calculated on the commonality of the machines in each block divided by the union of the set of machines in the blocks being compared. Blocks \( G_{1.1} \) and \( G_{2.1} \) have a similarity index \( J = 0.75 \) and they propose an evolving machine group of \( \{ M_1, M_2, M_3, M_4 \} \) to \( \{ M_1, M_2, M_3 \} \). Blocks \( G_{1.2} \) and \( G_{2.2} \) have a similarity index of \( J = 0.6 \) and they propose an evolving machine group of \( \{ M_5, M_7, M_8 \} \) to \( \{ M_4, M_5, M_6, M_7, M_8 \} \). There are three distinct characteristics of this new solution versus the legacy solution:

1) there are now two intra-cell movements instead of three;
2) it is apparent that machine \( M_6 \) is only required in the second time period;
3) there is a migration of machine \( M_4 \) from one evolving cell to another.

This variation on legacy cell formation methods therefore has the potential to provide better work flow in a time period and promotes delayed capital investment in machinery by allowing cells to reconfigure or evolve their machine-part grouping.

5. Optimization of Initial Solutions

The concept of allowing cells to evolve their machine-part group over a period of time creates new optimization problems that must be solved for the concept to become economically feasible. Consider that over a period of 5 years and a quarterly reconfiguration cycle, up to 20 unique machine-part group solutions may exist. The challenge is to merge these solutions into viable evolving cells as all proposed evolutions may not make practical or economic sense.

**Optimization Problem One – The immovable machine constraint**

After evolving cells have been proposed in the immovable machine constraint must be applied. In order to determine the host cell for an immovable machine one must consider all machine-part groups visited by it in the preliminary solutions. The host cell can then determine by the cell that would otherwise incur the highest intra-cell material handing cost. The material handing cost of not having the immovable machine in a cell may be determined as follows:

\[
CM_x = \sum_{T=1}^{n} k_T Q_T \tag{7}
\]

Were \( CM_x \) is the intra-cell material handling cost of not locating the immovable machine in cell \( x \) over the lifetime of the system; the cost in each time period \( T \) is estimated by a material handling cost per part, \( k_T \), in that period and the volume of parts \( Q_T \) making the related intra-cell. The volume \( V_T \) may be forecast by relating the relevant curve on the Norton-Bass model to appropriate entities in the BOM. The material handling cost per part has also been described by time dependant variable \( k_0 \), allowing the cost to be related to inflation over a number of years.

**Optimization Problem Two – Minimization of machine migration**

After the immovable machine constraint has been applied to the preliminary evolving machine-part groups, all machine migrations must be examined as some of these migrations may be eliminated for economic reasons. The optimization problem is to determine which migrations to eliminate such that the cost of machine migration (reconfiguration by machine movement) is at a best compromise with the cost of moving parts between cells. The solution method is illustrated with an example:

**Example:**

If the number of migrations for a machine \( M_i \) is \( n \) in the proposed solution; the solution can be encoded in a binary string of length \( n \). If the migration is approved the bit value corresponding to the
migration is 1, if it is denied the bit is 0. The number of possible solutions will therefore be $2^n$. The best solution for small problems can be found by exhaustive search and by a genetic algorithm for larger problems. Genetic operators for binary strings are well documented and will not be discussed here. Consider the example shown in Table 1 below, which has seven migrations across eight time periods, therefore the number of possible solutions is 128. $C_T$ is the cost of moving a machine in time period $T$, $k_T$ is the material handling cost per part in time period $T$ and $Q_i$ is the quantity of parts from each of three cells $X$, $Y$ and $Z$ that require access to the machine in question. The explicit quantities $Q$ can be determined from the Norton-Bass forecast in each time period.

Table 1: Symbolic Example of Machine Migration Problem

| Time, T | Proposed Resident Cell | Migration, i | $C_T$ | $k_T$ | $Q_{xi}$ | $Q_{yi}$ | $Q_{zi}$ |
|---------|------------------------|--------------|-------|-----|---------|---------|---------|
| 1       | X                      | 0            | $C_1$ | $k_1$ | $Q_1$   |         |         |
| 2       | Y                      | 1            | $C_2$ | $k_2$ | $Q_2$   | $Q_3$   |         |
| 3       | X                      | 2            | $C_3$ | $k_3$ |         | $Q_4$   |         |
| 4       | Z                      | 3            | $C_4$ | $k_4$ |         |         | $Q_5$   |
| 5       | Y                      | 4            | $C_5$ | $k_5$ |         |         | $Q_6$   |
| 6       | X                      | 5            | $C_6$ | $k_6$ |         |         | $Q_7$   |
| 7       | 3                      | 6            | $C_7$ | $k_7$ | $Q_8$   | $Q_9$   |         |
| 8       | 1                      | 7            | $C_8$ | $k_8$ | $Q_{10}$|         |         |

The solution is encoded in a binary string and the quality of the string is determined by decoding and evaluating it using equation (8). The solution is decoded using binary activity coefficients $X_i$, $Y_i$, $Z_i$ and $x_i$, $y_i$, $z_i$ for proposed and final solutions respectively. If the coefficient $X_i = 1$, this means that machine $M$ is present in that cell (group) in the $i^{th}$ period, in the preliminary solution. If $x_i = 1$, this means that the machine is also present in that cell (group) in the final solution. Consider the decoding shown in Table 2, where areas shaded in grey are populated from Table 1. $B_i$ is the bit value corresponding to the approval/rejection of the $i^{th}$ migration.

Table 2: Decoding Solution to Obtain Final Machine Migration

| Time, T | Proposed Intra-cell Migrations of $M_i$ | Approved/ Rejected | Final Intra-Cell Migrations of $M_i$ |
|---------|----------------------------------------|-------------------|-----------------------------------|
| $T$     | $i$ | $X_i$ | $Y_i$ | $Z_i$ | $B_i$ | $x_i$ | $y_i$ | $z_i$ |
| 1       | 0   | 1     | 0     | 0    | 1     | 1     | 0     | 0     |
| 2       | 1   | 0     | 1     | 0    | 0     | 1     | 0     | 0     |
| 3-4     | 2   | 1     | 0     | 0    | 1     | 1     | 0     | 0     |
| 5       | 3   | 0     | 0     | 1    | 1     | 0     | 0     | 1     |
| 6-7     | 4   | 0     | 1     | 0    | 0     | 0     | 0     | 1     |
| 8       | 5   | 1     | 0     | 0    | 0     | 0     | 0     | 1     |
| 9       | 6   | 0     | 0     | 1    | 1     | 0     | 0     | 1     |
| 10      | 7   | 1     | 0     | 0    | 0     | 0     | 0     | 1     |

From the example above, the binary string 0110010 ultimately yields two migrations for machine $M$. The machine remains in group (cell) $X$ for time periods 1-4 and then migrates to group (cell) $Z$ for time periods 5-10. This reduction in machine migration will be at the expense of increased intra-cell movement of parts. The quality for this solution is evaluated against the objective function below, which aims to minimize the total cost considering machine movement and intra-cell movement of parts:

$$
\min \sum_{i=1}^{n} B_i C_i + k_i (x_i Q_{Xi} + y_i Q_{Yi} + z_i Q_{Zi})
$$

(8)
Once the immoveable machine constraint and the optimization of machine migrations has been performed on preliminary solutions, the final result is a set of evolving machine part groups that may be used to design reconfigurable manufacturing cells. The concept of an evolving manufacturing cell has shown the potential to reduce intra-cell movements and possibly eliminate the duplication of capital equipment (machines and material handling equipment) in a manufacturing system.

6. Conclusion

This paper has presented the concept of evolving machine-part groups as a type of group technology for cell design within the scope of Reconfigurable Manufacturing Systems. A RMS is a system that changes its structure in order to meet changes in production requirements. The concept of an evolving machine-part group provides the underlying framework that guides how the structure should be reconfigured, taking into account changes in part mix, while optimising the system for better part flow and utilization of available capital equipment. The framework utilizes a variation on existing group technology methods to propose the migration of machines from one manufacturing cell to another to provide the reconfiguration. Two methods were presented on how to filter proposed machine migrations for practicality and economic viability. Future work includes the development of line analysis tools for the physical layout design of manufacturing cells taking into consideration the foreknowledge on how the machine and part groups will evolve in that cell over time.

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