

# Automated Design of Reconfigurable Manufacturing Systems A Framework based on a Genetic Algorithm and Discrete System Simulation

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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 manufacturing design systems do not encapsulate concepts of reconfigurability in design mechanisms to obtain optimal RMS configurations. This paper presents a framework for a resource allocation and shop floor design system within the context of RMSs. The framework focuses on the automated generation of shop floor configurations for systems with high product variety and shared resources. The DEVS, (Discrete Event System Specification), formalism is used to model reconfigurable equipment and simulate manufacturing processes. The “design engine” in the proposed framework, implements a genetic algorithm for the assembly, evaluation and optimisation of candidate shop floor configurations and their corresponding DEVS models.

## 1 INTRODUCTION

The concept of Reconfigurable Manufacturing was first proposed and formalised by researchers at the University of Michigan in the late 1990s. A definition of Reconfigurable Manufacturing Systems as follows (Koren et al., 1999): “ 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 inadequacy of previous manufacturing paradigms in addressing 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 (Malhotra et al., 2009). In order to address these challenges RMSs are envisioned to exhibit transformable system layouts, reconfigurable processes, cells and machines. Reconfigurability in RMSs is also specified to be achieved by the use of modular mechanical hardware and control elements

that can be rapidly integrated into Reconfigurable Machine Tools (RMTs), material handling systems, quality control systems and product assembly mechanisms to achieve new levels of system functionality (Moon and Kota, 2002, Mehrabi et al., 2000).

The nature of RMSs presents the necessity to quickly alter factory floor configurations when the system can no longer meet the demands of the production schedule. The generation of RMS configurations that facilitate alterations to its machines is essential to maintaining system productivity under changing production demands. Existing manufacturing design systems do not encapsulate concepts of reconfigurability in design mechanism to obtain optimal RMS configurations. This paper presents a framework for an automated resource allocation and shop floor design system for RMSs.

## 2 RELEVANT LITRATURE

A method for the design of a RMS was presented by (Koren and Shpitalni, 2010). The method extends to the design of a RMS configuration for a single part

family. The first stage in the method is a calculation of the number of machines required to complete an operation. The number of machines  $N$ , may be arranged in a variety of different configurations. The minimum number of stages in a configuration is limited to the number of machine setups required to produce the part family. Koren's method requires the manual population of a space of potential configurations. The selection of an optimal configuration then proceeds by eliminating those configurations that cannot meet the required production rate. Consideration is also given to system throughput with machine reliability less than 100%, investment cost, scalability and floor space. Koren and Shpitalni presented a manual method of enumerating and evaluating candidate RMS configurations. The number of configurations that  $N$  machines may assume, grows factorially with the number  $N$ . This method therefore requires substantial amounts of time and human effort to enumerate and evaluate different configurations.

The use of the Analytic Hierarchy Process, (AHP), was proposed by (Abdi, 2005) for the design of a suitable RMS. The AHP was originally developed by Thomas L. Saaty and the details of this algorithm may be found in (Saaty, 2008). The AHP requires a set of 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 implementation presented by Abdi required the manual enumeration of possible RMS design configurations. This method, like (Koren and Shpitalni, 2010), is unappealing due to the time required to enumerate and rank various configurations.

The use of a Genetic Algorithm to design a Multiple Part Line (MPL) for RMSs was proposed by (Tang et al., 2003). Tang defined a MPL as a line that consists of several serial stages with a finite size buffer between every two stages. Each stage consists of identical machines in parallel that perform the same set of tasks. The problem formulation restricted the MPL to the production of a given part family. It was assumed that the number of stages in the MPL is predetermined by the designer and each

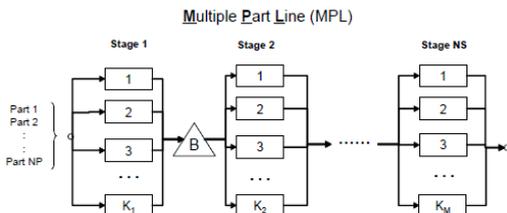


Figure 1: Illustration of a Parallel MPL (Tang et al., 2003).

part visits every stage in the MPL. The objective of the optimisation was therefore, to allocate machines to the various stages of the MPL from a given library of available machines. Limitations in this GA implementation include the specification that the RMS layout assumed a form as depicted in Figure 1.

### 3 PARALLEL DEVS SIMULATION

The use of computer simulation for the design of RMSs has been largely overlooked. This research pursues the use of simulation for manufacturing system design within an automated framework. The Parallel Discrete Event System (Parallel DEVS) specification has been chosen as the formalism for the simulator. DEVS was selected because the formalism is hybrid, i.e capable of modelling both discrete event and discrete time systems. The formalism is also modular and hierarchical thus making it suitable for creating manufacturing system models that can be generated and modified automatically during the execution of a genetic algorithm. The Parallel DEVS variation of the original DEVS formalism was introduced (Chow and Zeigler, 1994). A Parallel DEVS model consists of Atomic Models that are networked to form coupled models. An Atomic DEVS model  $M$  is an 8-tuple defined by:

$$M = \langle X, S, Y, \delta_{int}, \delta_{ext}, \delta_{con}, \lambda, ta \rangle$$

Where:

- $X$ : is a set of input events;
- $Y$ : is a set of output events;
- $S$ : is a set of sequential states;
- $\delta_{ext}: Q \times X^b \rightarrow S$ , is an external transition function; where  $Q = \{(s, te) | s \in S, 0 \leq te \leq ta(s)\}$  is the total state set of  $M$  and  $te$  is the time elapsed since the last the last event;
- $\delta_{int}: S \rightarrow S$ , an internal transition function;
- $\delta_{con}: S \times X^b \rightarrow S$ , is the confluent transition function;
- $\lambda: S \rightarrow Y^b$ , is an output function;
- $ta: S \rightarrow Real$ , is the time advance function.

Atomic DEVS models have been used to model the elementary components of a manufacturing system such as buffers, machines, assembly stations, human labourers, robots and material transport systems. Atomic models are stored in a manufacturing resource/ equipment library:

$$LIB = \{M_1 \dots M_n\}$$

Atomic models from this library are selected to create candidate design solutions for a

reconfigurable manufacturing system. A candidate design solution is a network of atomic models, which, as a whole is a discrete system model of a manufacturing system. The structure of a coupled model according to the Parallel DEVS formalism is:

$$DN = \langle X, Y, D, \{M_i\}, \{I_i\}, \{Z_{i,j}\} \rangle$$

Where:

$X$ : is a set of input events;

$Y$ : is a set of output events;

$D$ : is a set of component names  $\{i\}$ ;

$\{M_i\}$ : is a set of atomic components,  $\{M_i\} \subseteq LIB$

$\{I_i\}$ :  $I_i$  is the set of other atomic models, by name, that influence the  $i^{th}$  atomic model

$\{Z_{i,j}\}$ : is the set of input and output couplings

The structured population of the 6-tuple coupled model to create viable candidate manufacturing system configurations requires the use of a reconfigurable process plan used in conjunction with a selection and organisation strategy.

## 4 RECONFIGURABLE PROCESS PLANS

A Reconfigurable Process Plan, unlike a traditional process plan, is a set of all possible mappings between a part feature and the variety of machines that are available to create that feature. The most elementary building block of a reconfigurable process plan is a process descriptor. A process descriptor  $P_{i,j,k}$  is used to represent information pertaining to the creation of feature  $k$  on a part, using machine  $i$  in configuration (setup)  $j$ . Recall that the machines available to RMSs are reconfigurable, this is discussed in (Moon and Kota, 2002, Padayachee et al., 2009). The description  $P_{i,j,k}$  is a 3 – tuple defined by:

$$P_{i,j,k} = \langle tm, q, c \rangle$$

where:

$tm$ : is the time for part feature  $k$  to be completed on machine  $i$  in configuration  $j$ ;

$q$ : is the feature quality confidence on machine  $i$  in configuration  $j$  ( $0 < q < 1$ );

$c$ : is the cost of machining feature  $k$  on machine  $i$  in configuration  $j$ .

The process descriptor therefore assists automated resource allocation by presenting a mapping between a part feature and a machine, as well as the information that may be used to evaluate the optimality of the relationship.

RMSs will contain multiple types of reconfigurable machinery capable of providing

similar processing operations. Therefore the creation of a feature on a part may be achieved by a variety of machines with different setups; the number of possibilities may be encapsulated in a set:

$$F_k = \{P_{ijk}\}$$

The set of feature may then be grouped to represent an entire part; this may be written as an ordered set, where the precedence of feature creation is according to a prescribed sequence:

$$PART_m = \{F_k\}$$

$$FAMILY_n = \{PART_m\}$$

$$PLATFORM_o = \{FAMILY_n\}$$

Parts may also be grouped into part families, and part families into product platforms (a family of assemblies) as described above. The set  $PLATFORM_o$  is a set of all possible process plans and corresponding resource allocations for a product platform.

## 5 CANDIDATE RMS CONFIGURATIONS

Candidate RMS configurations are generated by first selecting a process descriptor for each part feature  $F_k$ . Once a process descriptor has been selected for the creation of a part feature, the corresponding machine is selected from the set  $LIB$ . The allocation (final mapping) of machines to part features is stored in a set called  $MAP$ . One  $MAP$  exists per part family. This process is performed repeatedly until all features on all parts to be manufactured have had a manufacturing resource allocated to them. A flow chart of the procedure is illustrated in Figure 2.

Multiple part features, on parts from the same family, may be created by the same type of machine (possibly with the same setup). Such features are grouped into Operational Groups ( $OG$ ). The machines on which an  $OG$  is executed are grouped for further analysis:

$$OG_u = \{ \langle P_{ijk}, M_i \rangle, \dots \}$$

In an  $OG$ , the feature number  $k$  and the setup (configuration) number  $j$  of the process descriptors change but the machine number  $i$  stays the same. The elements of an  $OG$  are further divided to form smaller Operational Clusters ( $OC$ ), i.e.  $OC \subset OG$ . Formation of operational clusters depends on features requiring the same type of setup on the same type of machine. Because RMSs allow dynamic changes to machines and setups,

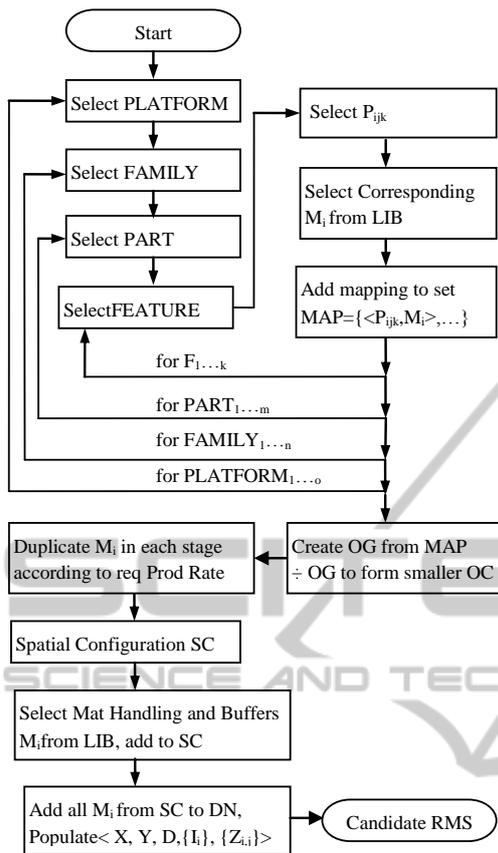


Figure 2: Process for Generating Candidate RMSs.

operational clusters may also be allowed on a machine where the required setup change is minimal between parts.

Machines in an *OC* are then duplicated until the set of machines forms a *STAGE* able to provide the required daily production rate. Multiple stages are then spatially arranged according to a prescribed sequence of operation:

$$SC_v = \{STAGE_1, \dots, STAGE_u\}$$

The Spatial Configuration of stages (*SC*) will correspond to one part family and its block of manufacturing lines. The block of manufacturing lines that are described by *SC* may be translated in to facility layout diagrams as illustrated by Figure 3.

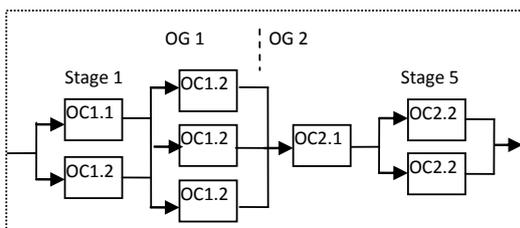


Figure 3: Spatial Configuration of a Block of Lines.

Multiple blocks of manufacturing lines such as those illustrated in Figure 3 will be placed on the factory floor for each part family in the system. All lines will eventually lead to assembly stations. Facility layout for assembly lines constitutes future work and is not considered in this paper.

## 6 OPTIMISATION STRATEGIES

### 6.1 Feature – Machine Mapping

The design of a RMS may be optimised at multiple levels using various modifications. The first modification that can be made to the design is changing the mapping between a part feature and the machine used to make it. This will require the complete redesign of the entire block of lines in which that feature is created. Changing the machines used to create a feature would usually require swapping machines between other blocks of lines, unless the library of manufacturing equipment has excess machines of an appropriate type available (practically unlikely). A single modification of this type therefore has the ability to cause great changes in a candidate solution. This type of modification is therefore unsuitable as an optimisation mechanism. A rule, algorithm (e.g. the Analytic Hierarchical Process) or heuristic should be used for selecting the most appropriate machine to create a feature at the outset and once a mapping has been established it should not be altered as an optimisation mechanism.

### 6.2 Operational Clusters, Stages and Blocks

The division of operational groups into clusters, the formation of stages from clusters and the arrangement of stages into blocks of manufacturing lines, is sizeable combinatorial optimisation problem. The operational group will need to be divided across multiple stages such that:

- the production rate under a static production schedule is optimal,
- flow is balanced between different stages,
- the production rate is least diminished when reconfigurations are required as per a dynamically changing production schedule.

Finding an optimal configuration for a block of lines, and considering that a manufacturing system would consist of multiple blocks; the colossal task of finding an optimal configuration for all blocks would be a process that is best automated by a

suitable algorithm.

## 7 OPTIMISATION ROUTINE

### 7.1 Genetic Encoding

As a first initiative in the development of an automated design system for RMSs, the authors propose that the optimisation of the design be executed within the structure of a Genetic Algorithm. Encoding for an operational group and its corresponding operational clusters is a binary matrix of links between machines and features:

$$OG = \begin{matrix} & 1 & \dots & k \\ \begin{matrix} 1 \\ \vdots \\ n \end{matrix} & \begin{bmatrix} ? & \dots & ? \\ \vdots & \ddots & \vdots \\ ? & \dots & ? \end{bmatrix} \end{matrix}$$

Each row of the matrix represents machines from 1- $n$  and each column, the features that could be created on those machines from 1- $k$ . Blocks of operational group lines are stored in the ordered set *BLOCK*.

$$BLOCK = \{OG_1, \dots, OG_x\}$$

### 7.2 Genetic Operations

Standard genetic operations are gene mutation and crossover. For gene mutation pair wise “bit flipping” of elements in an operational group matrix is performed. The operation is pair wise because once a feature has been assigned a new operational cluster within a group, its assignment to another cluster must be deactivated.

For genetic crossover to be performed in a meaningful way, while still maintaining the integrity of a candidate solution, this operation has been restricted to swapping of ‘OG’ elements from one *BLOCK* set with those from another *BLOCK* for the same part family.

### 7.3 Execution of Algorithm

The execution of the Genetic Algorithm begins with the creation of an initial set of candidate solutions as per the routine outlined in Section 5. When an initial set of candidate solutions have been created the encoding of the solution must be represented in two formats; a format that may be used to construct DEVS models and a genetic encoding. DEVS coupled models are assembled and simulated to produce results that may be analysed and used for fitness evaluations. The use of simulation as part of

the optimisation procedure is essential for examining the effect that reconfiguration will have on the production rate for different *OG* and *BLOCK* configurations. Simulation will also help identify zones of buffer over flow, buffer starvation and unacceptable machine idle times and idle frequencies. Data analysis of simulation results therefore has the ability to be used to exactly exploit problematic areas by means of genetic operators. However, a balance between solution exploitation and exploration must be observed to prevent premature convergence of solutions onto local minima.

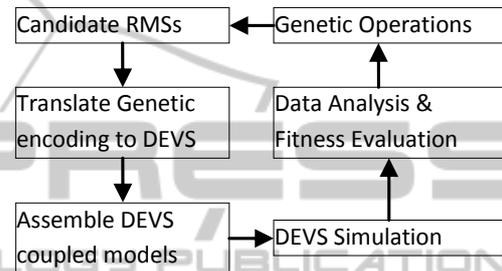


Figure 4: Execution Cycle for Genetic Algorithm.

A performance metric for a block of lines would be the ratio of reconfiguration sensitivity to cost. Reconfiguration sensitivity is an indicator of the effect of reconfigurations on the productivity of a block of lines. A suitable formulation and method of determining reconfiguration sensitivity constitutes future work.

Once candidates have been selected for genetic operations and these operations have been applied to create modified solutions; the genetic encoding must be translated into new DEVS models for the next iterative cycle. This cycle is shown in Figure 4, and continues until no significant improvement is demonstrated between successive iterations.

## 8 CONCLUSIONS

The framework presented in this paper requires significant software development for the full automation of the design system. A major component of future work will include the software development of the automated RMS configuration generator and DEVS model assembler. The software implementation will be built on the modeling formalism presented in Section 3, the concept of reconfigurable process plans presented in Section 4 and the routine presented in Section 5.

The exploration of appropriate Genetic

Algorithm configurations will also be conducted. This will include research into advanced performance metrics, improves genetic recombination techniques and offspring selection strategies. This research is necessary to ensure the implementation of an algorithm that does not converge prematurely on to sub-optimal RMS configurations.

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