Classification of Reconfiguration Resources and Lead Time for Reconfigurable Manufacturing Systems

Erik Puik[1*], Daniel Telgen[1], Leo van Moergestel[1], and Darek Ceglarek[2]

[1]Research Centre for
Technology and Innovation
HU University of Applied Science
Utrecht, 3500AD, the Netherlands

[2]International Digital Laboratory WMG
University of Warwick
Coventry, CV4 7AL, UK

Abstract

Manufacturing technology can improve the turnover of a company if it enables fast market introduction for volume production. Reconfigurable equipment is developed to meet the growing demand for more agile production. Modular reconfiguration, defined as changing the structure of the machine, enables larger variation of products on a single manufacturing system; these solutions are called Reconfigurable Manufacturing Systems (RMS). The quality of RMS, and the required resources to bring it to reliable production, is largely determined by a swift execution of the reconfiguration process. This paper proposes a method to compare alternatives for the ways to implement reconfiguration. Three classes of reconfiguration are defined to distinguish the impact of the proposed alternatives. The procedure uses a recently introduced index method for development of RMS process modules. This index method is based on the Axiomatic Design theory. Weighing factors are used to calculate the resources and lead time needed to implement the reconfiguration process. Application of the method leads to quick comparison of alternatives in the early stage of development. Successful execution of the method was demonstrated for the manufacturing process of a 3D measuring probe.

1. Introduction

Increasing global competition in manufacturing technology puts pressure on lead times for product design and production engineering. Quickly eroding markets, like markets for high tech systems and micro technology, especially require tight scheduling of system development; 'being first' leads to an extended economic lifecycle, better market penetration and higher added value for products. Together it will lead to higher return on investments [1]. By the application of effective methods for systems engineering (or engineering design), product design, and production, the development process can be executed in parallel instead of sequentially. Modular equipment is currently under development to meet the manufacturing demand of product families rather than single products [2-4]. Reconfigurable Manufacturing Systems (RMS) reuse modular parts or 'Process Modules' as building blocks for manufacturing systems [5]. RMS are a logical addition to 'Dedicated Manufacturing Systems' (DMS), 'Adjustable Manufacturing Systems' (AMS) and 'Flexible Manufacturing Systems' (FMS). DMS are most traditional; they are applied for a long period of manufacturing without significant changes, even up to 30 years. AMS and DMS are alike, but AMS are equipped with an increased number of tools that can be changed to address a broader scope of products. FMS are computer numerically controlled systems. The computerised control system enables fast adaptations to a range of variations in production. However, the structure of the machine was determined by the mechanical system design and is not able to change afterwards. RMS fill the gap by adding a modular architecture in both mechanical design and control system [6, 7].

Reconfiguration of RMS needs to be planned ahead. New systems in some cases can be assembled by solely reusing existing process modules. However, in the majority of situations this is not possible because product-specific modules need to be developed, or modules that are well specified are applied outside their specified operating window. Both situations cause additional risks in the configuration process of the RMS. Sloppy and/or hasty engineering efforts lead to questionable quality of the modules. The result is poor performance when production is ramped up. This paper presents a classification method that inventories and quantifies risks when planning the configuration of an RMS. The method can be applied as a systems engineering tool. Alternative equipment layouts can be effectively compared to classify their impact on resources, time and uncertainty.

[*] Corresponding author: Tel.: +31 651554041; E-mail: erik.puik@hu.nl

2. Definition of Reconfiguration Classes

An analytical comparison of manufacturing systems (DMS, AMS, FMS & RMS) was made by Zhang et al. [7]. Given systems were rated on 'Adaptability' and 'Reconfiguration Time' as shown in figure 1.

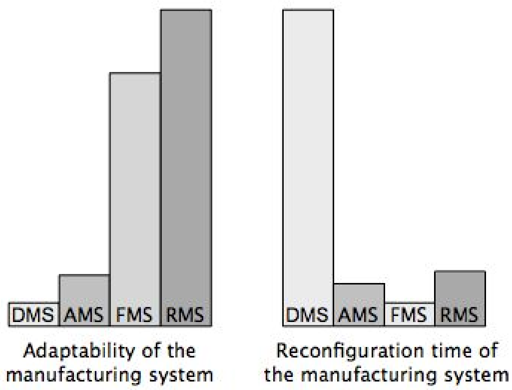

Figure 1. Adaptability of (left) and reconfiguration time of manufacturing systems (right).

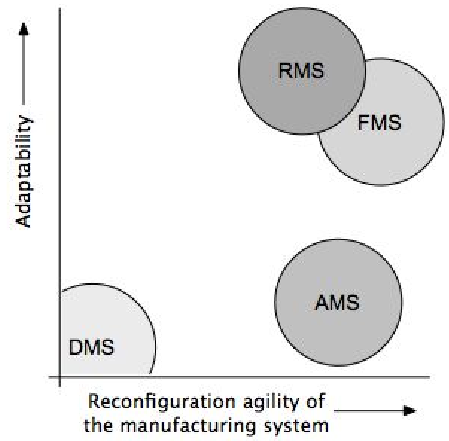

Figure 2. Comparison of DMS, AMS, FMS and RMS. Note that the horizontal axis is reversed compared to figure 1.

The overview in figure 2 was obtained by combining the data in a two dimensional representation. As expected, RMS score good on adaptability; changing the structure of the system adds broader possibilities for implementation of optimised process technology. RMS are not adapted as quickly as FMS, change of structure comes with more overhead than change of software. However, the exact position of the RMS in the graph can vary depending on the kind of reconfiguration. The time for implementation will be shorter if reconfiguration takes place with known and tested process modules if compared with a situation in which new process modules need to be developed. To distinguish the alternative scenarios, the following three classes have been defined:

a. Repeat: Process modules have been applied in the past and are well documented, processes are used within their specified operating windows;
b. Adapt: Process modules have been applied in the past and are well documented, processes are used outside defined operation windows or in an alternative manner that has not been tested;
c. Expand: Process modules do not exist yet and have to be developed (the library of modules is expanded).

It is possible to have a combination of classes since reconfiguration often requires more than a single module to be changed.

3. Classification of the Reconfiguration Process; Resources & Lead Time

3.1. Indexing Process Modules by using the Axiomatic Design Methodology

An index method was recently proposed to monitor the development of reconfigurable process modules [8]. The method divides the development procedure in a sequence of seven stages. The index process is based on the 'Axiomatic Design' (AD) methodology as developed in the late 70s at MIT [9]. The method uses 'Domains' to indicate different worlds of the designer as shown in figure 3. The domains in which functional requirements (FR), design parameters (DP) and process variables (PV) are represented as vectors are interrelated with design matrices, starting with the design equations according to good AD practice

$$\{FR\} = [A] \cdot \{DP\} \tag{1}$$

$$\{DP\} = [B] \cdot \{PV\} \tag{2}$$

where [A] & [B] are the product- and process-design matrices. If a product design has three FRs and three DPs, the product-design matrix has the following form

$$[A] = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad (3)$$

and a good design would be 'Uncoupled' or 'Decoupled' if the matrix is diagonal or triangular. The relation between DPs and PVs is determined by matrix [B] analogue to matrix [A].

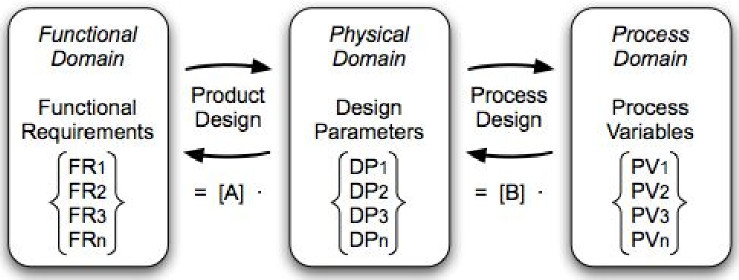

Figure 3. Axiomatic domain structure. The functional domain, the physical domain and the process domain are mapped with vectors that indicate relations. The FRs represent what the product should do, the DPs how it is physically achieved and the PVs how the physical system is realised.

The vectors and all elements of matrix [B] should be known for a good design of a reliable process module. This means that all process design equations are fully understood. The index method defines three major activities: It starts with decomposition to determine a full set of design equations. This is followed by a realisation stage in which the matrix is decoupled. The index method is completed with a test sequence. The sequence scans the operating windows of respectively the modules and the system to verify that no elements of the design matrices were missed. Around these activities, a framework with seven levels of completion is wrapped. The index levels are shown in figure 4. The development progress is monitored from left to right. The levels are self explanatory as they are based on axiomatic definitions. The goal is to reach the level of 'Functional System'.

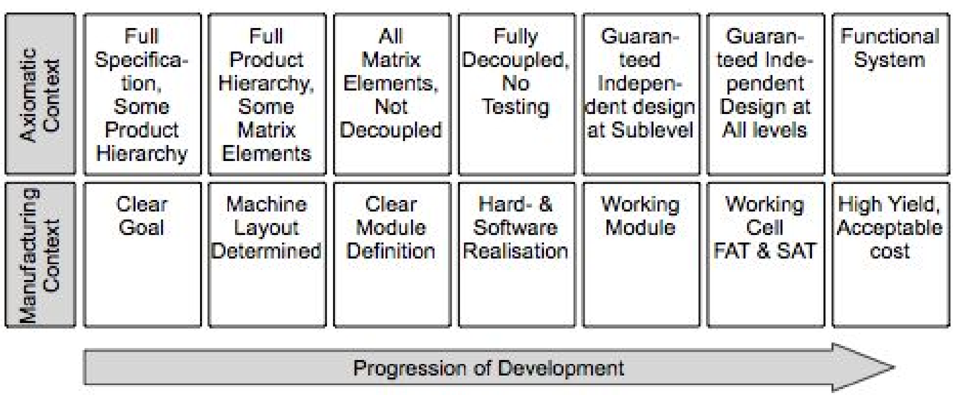

Figure 4. Development of RMS in seven steps from the embryonic stage to a complete and independent design. Progress is monitored from left to right. The axiomatic context as based on the matrix is also represented to the manufacturing domain.

3.2. Classification of Reconfiguration Schemes; Repeat, Adapt, Expand

a. The system's reliability will need effort to come up to standard after completion of RMS reconfiguration. A reconfiguration that 'Repeats' application of known and tested modules, which might be considered as the most moderate change, will cause the index level to drop to 'Guaranteed Independent Design'. Successful testing will bring the RMS up to the final level again. It does not matter if a single or a larger number of modules are replaced; system level tests are always required to bring the system back to production level;

b. The classification of the reconfiguration type ‘Adapt’ needs examination of the definition. It states ‘process modules are applied in the past but are used outside operating windows’ which means that all prior testing becomes obsolete. Unfortunately, the set back goes further than that; if the construction or software code to control the module requires changes, the realisation phase has to be completed again. This sets module development back to ‘All Matrix Elements Known but not Decoupled’;
c. Reconfiguration type ‘Expand’ per definition needs to go through all development levels of the index method as the index method was designed for new module development.

3.3. Resources & Lead Time

The total resources needed for reconfiguration can be calculated by summarising the effort to integrate all modules. This is done by summarising the total number of index-steps for all new modules of the reconfigured RMS. It provides a final score, expressed as resource-‘units’, according to

$$\sum_{i=FirstModule}^{LastModule} Units_i \tag{4}$$

that represents the resources needed for reconfiguration. Next, the lead time is determined by the longest development trajectory of any of the new process modules. This is done by taking the upper bound of all lead times according to

$$\max\left\{Units_{FirstModule},..,Units_{LastModule}\right\} \tag{5}$$

and it should be noted that lead times for reconfiguration are never shorter that 1 unit, the time for integration and test of the overall system. If at least one module is adapted it will be 4 units and if at least one module is expanded this is 7 units (figure 4).

4. Case: Manufacturing of a 3D Measuring Probe

3D Measuring Probes are made for geometrical measurement of high tech products with high accuracies and small tolerances. The probes are applied in coordinate measuring machines to enable measurements in the nanometre domain [10]. The heart of the probe consists of a surface-micro-machined Silicon Die that contains sensitive strain gauges to convert mechanical nanometre movements to electrical signals. A stylus is applied to measure the object and subsequently transfer the sensing movement to the Die. A manufacturing process for a measuring probe (figure 5a) was investigated for manufacturing on an RMS platform (figure 5b).

Figure 5a. A 3D measuring probe for the nanometre domain.

Figure 5b. Commercial reconfigurable production platform for micro systems.

4.1. Reconfiguration of an RMS

A tailored pick & place system was configured from standard modular building blocks to manufacture the probe. Table 1 shows a list of modules that are needed to realise the manufacturing system. There are two options to build the RMS 1/ Applying a passive alignment for parts (option 1), and 2/ Using active alignment by application of a computer vision system (option 2). A future modification was foreseen; the manufacturing system needs to be converted to another product of the same family in a later stage. The vision system offers higher flexibility but also takes more development effort. A number of members within the family of products are expected in the next years.

Option 1		
Process Module	**Class**	**Units**
Base frame	Repeat	1
Manipulator	Repeat	1
Gripper	Adapt	4
Feeder A	Repeat	1
Feeder B	Repeat	1
Nest for carrier	Adapt	4
Alignment Body	Adapt	4
Resources (∑)		16
Lead-Time (max)		4

Option 2		
Process Module	**Class**	**Units**
Base frame	Repeat	1
Manipulator	Repeat	1
Gripper	Adapt	4
Feeder A	Repeat	1
Feeder B	Repeat	1
Nest for carrier	Adapt	4
Vision System	Expand	7
Resources (∑)		19
Lead-Time (max)		7

Modified Option 1		
Process Module	**Class**	**Units**
Base frame	Repeat	1
Manipulator	Repeat	1
Gripper	Repeat	1
Feeder A	Repeat	1
Feeder B	Repeat	1
Nest for carrier	Repeat	1
Alignment Body	Adapt	4
Resources (∑)		10
Lead-Time (max)		4

Modified Option 2		
Process Module	**Class**	**Units**
Base frame	Repeat	1
Manipulator	Repeat	1
Gripper	Repeat	1
Feeder A	Repeat	1
Feeder B	Repeat	1
Nest for carrier	Repeat	1
Vision System	Repeat	1
Resources (∑)		7
Lead-Time (max)		1

Table 1. List of modules for a manufacturing system with variations for passive and active alignment. Modified options show the actions to be taken to convert the system for a future product of the same family.

4.2. RESULTS

If development resources and lead time are considered, based on the first configuration cycle, option 1 would be preferred over option 2. This is caused by the lower development resources required and the shorter lead time for the reconfiguration to be completed (16/19 & 4/7). However, for future modifications, this is reversed (10/7 & 4/1). The vision system increases flexibility within families of products that give the RMS the flexibility of an FMS. After the second reconfiguration, both options are comparable (26/8), all further reconfigurations within the same family of products will be in favour of option two.

5. DISCUSSION AND CONCLUSIONS

5.1. CLASSIFICATION OF THE RECONFIGURATION PROCESS

The method has shortcomings, to be addressed hereafter, but performs well in comparing the options for reconfiguration of an RMS to meet the manufacturing demand of products. The classification is strongly relying on the axiomatic index method that has been proven to be scientifically vigorous. The index method can be laborious but the index drop, when process modules are redesigned, can be determined relatively easy and sound. Therefore, a quick and effective resource estimation of the impact of the redesign can be made. The integrity of the axiomatic design matrix acts as a determinative parameter for the impact on an existing process module. The integrity can be explored with little effort; it enables the method to be applied in dynamic environments, for internal or external quotations and for determining response times to market demand.

A weak point of the index method is the assumption that the amount of work is proportional to the number of index levels to bridge. The number of index levels is set as a constant measure for quantification. The absolute accuracy of the method indeed has its limitations; it would not guarantee a project to stay within budget. The accuracy is expected to be acceptable if the amount of repeated modules is high. Mainly for module expansion problems occur; not in particular due to the inaccuracy of the index method, but rather because of the discrepancy between the number of steps, risk and required resources. This should be further investigated.

In the applied definition, a ‘unit’ is a measure for resources as well as for lead time. The thought behind this is that development of processes can be accelerated by spending extra resources to the problem, but only within limitations. This is confirmed by the definition of the index model where levels are sequentially completed. In reality however, by increasing resources in number and quality the development process indeed can be positively influenced. This effect has not yet been built into this classification methodology.

The different ways of reconfiguration can be visualised in figure 2 using the classification method. The choice of the positions in the portfolio were based on the following reasoning:

- RMS Repeat; the RMS will almost be as flexible as an FMS, but is more adaptable because of the change of structure of the system;
- RMS Expand; its reconfiguration agility should be between DMS and AMS, but its capacity to adapt for product change will be superior;
- RMS Adapt will be between RMS Repeat and Expand, as well concerning reconfiguration agility as adaptability.

This will cause figure 2 to evolve to figure 6.

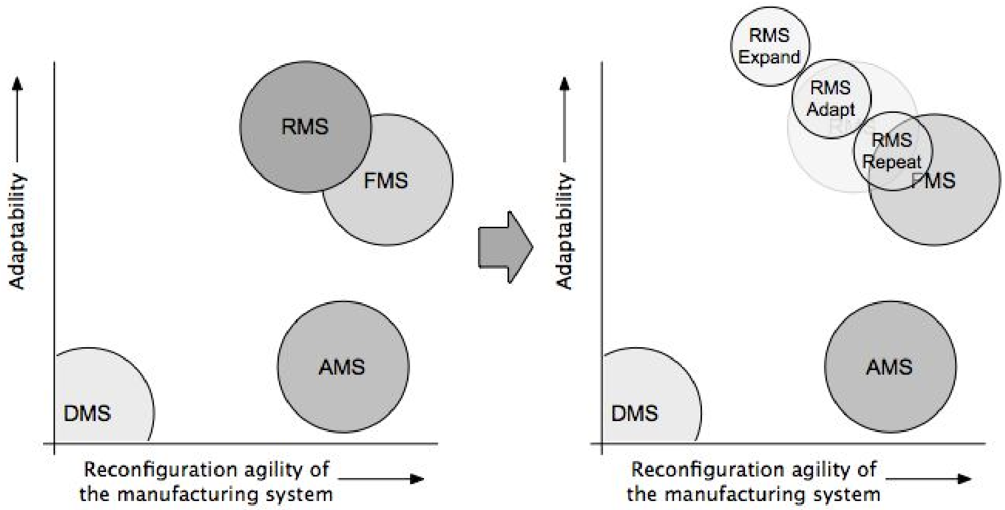

Figure 6. Different options for reconfiguration are determined by the character of the module change. A thorough change (RMS Expand) will lead to a larger response time but enables superior room for adaption. Conservative reconfigurations (RMS Repeat) are not as impressive from the perspective of adaption, but flexibility is comparable with FMS.

5.2. CONCLUSIONS

The Classification method for inventorying the reconfiguration of RMS, can be successfully applied to compare different solutions when reconfiguration is planned. The effective ways to quantify the impact on resources enables quick comparison for engineers and management. The results come available in the early stage of planning of the reconfiguration process when solutions for reconfiguration are not yet rooted and alternative options are still open.

ACKNOWLEDGEMENTS

This research was funded by MA3 Solutions, TNO Science & Industry, and the HU University of Applied Sciences in the Netherlands.

REFERENCES

[1] E. Puik and L. V. Moergestel, "Agile Multi-Parallel Micro Manufacturing using a Grid of Equiplets," presented at the International Precision Assembly Seminar, Berlin, Heidelberg, 2010, vol. 315, no. 32, pp. 271–282.

[2] Y. Koren, General RMS Characteristics; Comparison with Dedicated and Flexible Systems, no. 3. Berlin, Heidelberg: Springer Berlin Heidelberg, 2006, pp. 27–45.

[3] A. Gutierrez, "MEMS/MST fabrication technology based on microbricks: A strategy for industry growth," 1999.

[4] E. Puik, A. Rijfers, and L. Tillie, A lower threshold to the world, by combining a modular approach and a matching production framework. Proceedings COMS, 2002.

[5] M. Colledani and T. Tolio, "A Decomposition Method to Support the Configuration / Reconfiguration of Production Systems," CIRP Annals - Manufacturing Technology, vol. 54, no. 1, pp. 441–444, Jan. 2005.

[6] Y. Koren, U. Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy, and H. Van Brussel, "Reconfigurable Manufacturing Systems," CIRP Annals - Manufacturing Technology, vol. 48, no. 2, pp. 527–540, Jan. 1999.

[7] G. Zhang, R. Liu, L. Gong, and Q. Huang, "An Analytical Comparison on Cost and Performance among DMS, AMS, FMS and RMS," Reconfigurable manufacturing systems and transformable factories, 2006.

[8] E. Puik, E. Smulders, J. Gerritsen, B. V. Huijgevoort, and D. Ceglarek, "A Method for Indexing Axiomatic Independence Applied To Reconfigurable Manufacturing Systems," presented at the 7th International Conference on Axiomatic Design ICAD2013, Worcester, 2013, 1st ed., vol. 7, pp. 186–194.

[9] N. P. Suh, The principles of design. Oxford University Press, USA, 1990.

[10] H. Haitjema, J. K. van Seggelen, P. H. J. Schellekens, W. O. Pril, and E. C. N. Puik, "Metrology for MEMS; MEMS for Metrology," presented at the Procedures of the Memstand International Seminar, 2003.