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Towards practical guidelines for conversion from a fixed to a reconfigurable manufacturing automation system

Alan Coppini[a,b], Michael A. Saliba[a,]*

[a]*University of Malta, Msida MSD 2080, Malta*
[b]*Trelleborg Sealing Solutions Malta Limited, Hal-Far BBG 3000, Malta*

Abstract

It is generally considered to be a key requirement in the development of reconfigurable manufacturing systems, that economic feasibility is only attainable if the system is defined to be reconfigurable at the outset of its design. In this work we consider the potential exception to this requirement, in the context of a common industrial scenario where a specialized and expensive manufacturing machine or system will otherwise be rendered useless due to loss of business of the particular product being manufactured. Specific guidelines to convert from a fixed to a reconfigurable system are proposed, and evaluated through a case study.

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Keywords: Reconfigurable manufacturing systems; conversion guidelines; case study

1. Introduction

The changes in market demands witnessed in the past decades have had a significant effect on the manufacturing strategy employed. Previously, product life cycles were long and identical products were produced for the masses, resulting in the development and perfection of dedicated manufacturing lines famously pioneered by Henry Ford in

* Corresponding author. Tel.: +356-2340-2924 .
E-mail address: michael.saliba@um.edu.mt

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the early 20th century (e.g. [1]). In the early 1980's the concept of flexible manufacturing systems (FMS) was developed to cope with the transformation of consumer markets; shorter product life cycles and high product variety (e.g. [2]). Towards the end of the 20th century, the notion of reconfigurable manufacturing systems (RMS) appeared: living and evolving systems which are designed to be reconfigurable, to be quickly adaptable to changes in product requirements, and to be able to respond to customer requirements faster and more effectively [3].

Reconfigurable manufacturing systems aim at combining the high throughput of dedicated manufacturing lines with the flexibility of FMS, with the added ability to react quickly and efficiently to changes [3]. In addition to the above, they facilitate rapid system design, rapid conversion to new models, the ability to quickly and reliably integrate technology, and the ability to cater for varying product volumes with increased product variety [4]. In [4], the authors propose a set of distinguishing features, or key characteristics, which are requirements for a truly reconfigurable manufacturing system. A system which possesses all these characteristics is considered to have a high degree of reconfigurability. Reconfiguration can be initiated by a number of factors, such as variation in product demand, the introduction of new products, or the update of system components or integration of new components for improved productivity or improved quality. In the case of reconfiguration for new products or variation in demand, the process will begin at the system (i.e. top) level and propagate downwards [5]. The six core characteristics of RMS are considered to be *modularity* of the system hardware and software sub-components; *integrability* of the various current modules as well as of potential future modules; *convertibility* of the system for application to the manufacture of different products including future products; *diagnosability* with respect to the causes of quality and reliability problems; *customization* of the system hardware and software for the specific part family under consideration; and *scalability* of the system for rapid and economical changes in production capacity [4,6].

At either the system or machine level, two types of reconfiguration are recognized. Physical reconfigurability refers to the scalability of production volume, capacity and capability which is achieved by adding, removing or repositioning machines, machine modules or material handling systems. This approach is typically costly since it involves complex machines. Logical reconfigurability is any form of reconfigurability which can be employed without physical reconfigurability to achieve better agility. This includes flexibility of machines, operations, processes, routing, scheduling, planning and programming of manufacturing systems. This approach is less costly since it is achieved through good system and software design [6]. The industry also recognizes that reconfigurable machine tools (RMTs) are essential enablers of RMS; that reconfigurable assembly lines are, at least in theory, easier to achieve than RMS because of the less stringent tolerances; and that hybrid human-machine RMS are advantageous because they make use of the flexibility which is in-built in human nature but at a relatively low cost [6,7]. The study of reconfigurability in manufacturing extends to new approaches for control (e.g. [8,9]) and strategy (e.g. [10]).

A key requirement for an RMS is considered to be that its constituent systems and components must be designed to be reconfigurable from the outset, in order to adequately meet the core system characteristics of this paradigm [4,6]. It is emphasized that one must first define the part family of products, then address the appropriate system design issues, then link these to the corresponding machine design issues, and finally address methods to reduce reconfiguration and ramp-up times. Although this approach is understandable, it may not take into account the common situation when highly specialized machines become idle or underused due to loss of business of the particular product being manufactured. In such cases, it may in fact be advantageous to carry out a conversion project rather than scrapping the machine and buying another.

The conversion of a fixed automation system to an automated RMS is not considered in the literature and is identified as a research gap. The objective and contribution of this work is to explore this possibility and approach. A provisional set of systematic guidelines are proposed, to be used to convert a fixed automation system to a reconfigurable manufacturing automation system. The problem is approached by (i) taking note of the key requirements for reconfigurable systems (as summarized above); (ii) identifying the key shortcomings in reconfigurability of a generic fixed system; (iii) developing a formal set of generic guidelines, based on (i) and (ii) above, for conversion; (iv) applying the guidelines to an industrial case study; (v) carrying out an economic analysis of the proposed system; (vi) evaluating the application of the guidelines during the case study; and (vii) evaluating the proposed system with respect to reconfigurability requirements.

2. Development of the conversion guidelines

2.1. Requirements and limitations

A number of requirements for reconfigurability, found in the literature, have been identified as relating either to the system or to the machine level, and have been listed in Table 1. The table also gives an indication of the specific RMS characteristic(s) that are addressed by each requirement. The typical shortcomings of fixed systems with respect to reconfigurability involve the inability to meet these requirements, and in practical terms include limitations such as the following: (i) The system was designed for a specific part and cannot cater for similar parts within the same part family (lack of adjustability for product variants, e.g. in shape, materials, texture, colour); (ii) The system structure is fixed and cannot be easily adjusted (modules cannot be added without complex system redesign; the machine/component layout cannot be easily changed); (iii) The current system is not scalable (system capacity cannot be increased; an increase in capacity requires investment in a new machine); (iv) The system software is not adjustable (e.g. it does not allow for reprogramming of functions; the graphical user interface cannot be modified). The proposed guidelines for conversion to RMS involve the systematic assessment of each of the reconfigurability requirements, and the individual targeting of each limitation with specific solutions.

2.2. Step 1: Define the requirements for the RMS

The first step is to define the bounds of the conversion project; i.e. what portion of the entire manufacturing system will be targeted during the improvement project. At this point it is important to hold a discussion with all key stakeholders including representatives from marketing or sales, production, quality and product development. A

Table 1. RMS and RMT requirements and associated characteristics

	Requirement	Characteristic[1]					
		M	I	C	D	Cu	S
	System Level						
S1	System components are easily added and removed	✓	✓				✓
S2	Machines can be moved easily and quickly	✓	✓			✓	
S3	Electricity and plumbing connections allow movement of machines	✓				✓	
S4	Manufacturing system planning and monitoring software can be customised					✓	
S5	Parts are inspected on-line; either manually or automatically				✓		
S6	System can detect and correct production errors				✓		
S7	System can handle different parts from one part family with little to no down time			✓			
S8	System capacity can be increased quickly and easily						✓
	Machine Level						
M1	Machine components are easily added and removed	✓	✓				✓
M2	Machine elements can be switched/relocated within the same machine	✓				✓	
M3	Control system supports addition of components	✓	✓				✓
M4	Adding latest technological components is easily achieved		✓			✓	
M5	Machine components are customisable			✓		✓	
M6	Component control is customisable/open architecture			✓		✓	
M7	Machine can handle different parts from one part family with little to no change over			✓			
M8	Machine can detect and correct production errors				✓		
M9	Machine capacity can be increased quickly and easily						✓
M10	Machine has on-line part inspection				✓		

[1]M:modularity; I:integrability; C:convertability; D:diagnisability; Cu:customisability; S:scalability.

number of questions to be considered during the early stages of the reconfiguration process have been gathered from the literature search, particularly [11], [12] and [13]. This list is not exhaustive, however it helps direct the thought process during early discussions and thus can provide a good basis for defining the boundaries of the project:

- Is the demand for the product being produced forecasted to increase?
- Is it expected that different parts from the same product family will be processed on this line?
- Is the current production technology outdated or produces parts of inferior quality compared to competition or to customer requirements?
- What key product features are important to allow new products to be produced on the same system? Use of Design for Manufacturing techniques is important.
- What defines products from the current product family? In some cases it may not be viable to create a system which can cater for all parts within a current part family. Product families may need to be subdivided and reclassified accordingly.
- Is demand for the product or product family currently produced on this manufacturing system on the decline?
- What is the budget for converting the current fixed system?
- How will the down-time and production capacity lost due to the conversion process affect the company and the customers?

In this work a logical approach has been taken to categorize and address the inhibitions to reconfigurability at the system and machine levels as described in sections 2.3 and 2.4 below. The individual problems that may need to be solved are generic and are derived from Table 1, while the suggested solutions are based on intense discussion with engineering and technical personnel from the project development and quality departments of the partner company as well as from the shop floor. The lists are therefore not necessarily exhaustive and may also need to be adapted to the specific scenario under consideration. As indicated in Table 1, the guidelines are intended to address the attainment of the six core characteristics of RMS.

2.3. Step 2: Address the current inhibitions to reconfigurability at the system level

System components such as machines, material handling systems etc. cannot be added or removed. This may be due to a number of reasons listed below:

(i) System components are welded in place or bolted to the ground and thus cannot be moved.
Solution: Make use of quick release fasteners, rather than welding components to each other. If the machine is bolted to the ground for stability reasons, fix the machine to a sturdy base (concrete or steel) with wheels; which supports the machine but which can be moved around quickly.

(ii) System components are not fixed in place but require heavy lifting equipment to be moved, which is not readily available.
Solution: Air powered dollies allow for quick movement of machinery and require minimal capital investment. Such systems require the machine to be lifted before placing the dollies under it. The operator of the moving equipment uses a remote control to manoeuvre the machine to its new location. Alternatively air casters can be used which are designed to float heavy machinery across shop floors using a thin film of pressurized air, to bring down the coefficient of friction between the machine and the floor. Such systems can be permanently attached to each machine in the system to allow ease of machine movement. For this to work, the surface of the floor along which the machines will be moved must be smooth and free from large cracks or holes which would allow air to escape and result in a subsequent loss of lifting ability. When designing new machines or machine substructures, it is also recommended to look into the possibility of using lightweight composite materials for many discrete manufactured components. Aluminium composites can be used instead of cast iron; resulting in lighter components with better mechanical properties [14].

(iii) Support services such as electricity, plumbing, compressed air and network connections are fixed, limiting the ability to move machines around.
Solution: This issue can be overcome by having electricity, plumbing, compressed air connections and even network cables passing along an elevated structure above the shop floor. This structure will consist of a

number of connection points to which a machine can be connected via cables or pipes. The points should make use of quick connections to speed up the process of disconnecting and connecting machines. The use of these quick connections must be supported by standardization of each type of connection, e.g. all air connections on the shop floor should make use of the same male and female connections.

Production planning and product routing between different system components cannot be changed.
Solution: The production planning system may need to be updated to be able to choose the routing of the products on the shop floor. If the system will frequently be reconfigured with machines being moved around, it may be necessary to use a mapping system to make it easy for the users (shop floor personnel) to understand where to get products or material from and where to take them to. This can be achieved through mapping of the shop floor using a coordinate style system and including the locations in the job card.

Parts being produced in the system are inspected off-line and poor quality production is not immediately detected.
Solution: For a system to be reconfigurable it must be able to monitor the quality of the key characteristics of the products being produced. This can be done either manually or automatically, through statistical sampling or 100% inspection. The information may be used to guide machine setters, or be directly fed back into the system which modifies the system parameters to correct the problem.

The current system can only handle one part number, and changeover to other parts is lengthy and complicated.
Solution: The system design needs to be modified to be able to cater for different parts from the same part family. This can be achieved through intelligent redesign of the system components. An example of this would be a material handling system made up of components which can be easily adjusted for production of different parts.

Increasing capacity of current system requires duplication of the entire system.
Solution: To increase capacity, an analysis of the current process should be carried out to identify the bottleneck in the process. This system component can then be duplicated to increase the productivity and thus reduce or eliminate the bottleneck. Material handling systems between machines should be upgraded so that products from multiple machines can be handled by the system. In the case of multiple machines within the same manufacturing system, it is important to have the ability of parts to cross over between machines at each stage of the manufacturing process.

2.4. Step 3: Address the current inhibitions to reconfigurability at the machine level

Machine components are fixed and components cannot be added or removed. This may be due to a number of reasons listed below:

(i) The components were not designed to be changed (Physical constraints).
Solution: Redesign the machine components such as fixtures, spindles etc. so that these can be easily dismantled and replaced.

(ii) The system software and control architecture does not allow for changing the components connected to the machine (Logical constraints).
Solution: Redesign the system software/controller to be capable of handling additional components with minimal effort and changeover time. The use of wireless rather than point-to-point hard-wired connections will help improve the ability to move machine components.

(iii) Machine components are controlled by a single central control system.
Solution: Truly reconfigurable systems allow for seamless addition and removal of components (plug-and-play feature). Such technology has not yet become available but is being developed by a number of component manufacturers. The target is to have one small package which brings together transducing, network connectivity and the first level of control.

(iv) The control system has insufficient channels to cater for additional components which may are needed to cater for products from the product family.

Solution: Upgrade control system/interface to be able to cater for an increase in inputs as may be needed in the foreseeable future.

(v) Control of each major machine component is not possible.
Solution: Upgrade actuator, sensor and control system to be able to control each major component separately and easily.

Parts being produced on the machine are inspected off-line and poor quality production is not quickly detected.
Solution: For a machine to be reconfigurable it must be able to monitor the quality of the key characteristics of the products being produced. This can be done either manually or automatically, through statistical sampling or 100% inspection, either on-line or off-line, in-process or post-process.

The current machine can only handle one part number, and changeover to other parts is lengthy and complicated.
Solution: The machine and component design needs to be modified to be able to cater for different parts from the same part family. This can be achieved through careful re-design of the machine components and how these connect to the machine. The use of quick release mechanisms and collet chucks is preferred to use of nuts and bolts which are time consuming and prone to damage.

Increasing capacity of current machine is not possible.
Solution: The machine design needs to be modified to be able to cater for additional capacity.

2.5. Economic analysis

There are a number of anticipated financial benefits of operating a RMS, e.g. improved sales by responding to customer requirements faster than competition; improved production efficiency through integration of latest machine components; reduced scrap loss due to better diagnosability of production errors; increasing capacity requiring less capital investment since it can be achieved by duplicating machine components rather than entire machines or production systems. A cost breakdown of each proposed improvement must be prepared, to establish economic viability. The costs incurred may also include: engineering design costs, installation costs, additional special tooling, training costs as well as cost of lost production due to machine conversion downtime. Not all cost savings are easy to quantify; but at least an estimate can be made. For example, one can analyse how many request-for-quotation requests (RFQs) were rejected during a period due to the inability to produce the requested parts. Although responding to the RFQ would not imply that the contract would have been won, one can say that the potential for sales would be increased. A simpler example is estimating that the new system should give a specific production scrap loss (e.g. 2%) as opposed to the current system's (e.g. 5%). Thus it is more straightforward to evaluate whether the improvement is justifiable or not.

Capital expenditure appraisal for the project can be carried out using various methods such as break even or net present value (NPV) analysis (e.g. [15]). Application of the latter method entails carrying out projected calculations of setup savings, as well as of all other savings / losses, for every year of intended operation over the projected lifetime of the production system, and drawing up a chart as indicated in Table 2. The actual values for every year are discounted by a factor that is determined by the company's cost of capital, as per equation (1), so that all savings and losses are normalized to an appropriate NPV. A positive total NPV suggests that the project is economically feasible.

$$\text{Discount factor} = \frac{1}{(1+r)^n} \tag{1}$$

where r = cost of capital; and n = number of years since start of project.

Table 2. Template for the application of the NPV method for economic appraisal, for a projected project lifetime of *N* years.

Year	Description	Value	Discount factor	NPV
		€		€
0	Total outlay			
0	Initial savings			
1	Setup savings			
1	Personnel savings / losses			
1	Other savings / losses			
2	Setup savings			
2	Personnel savings / losses			
2	Other savings / losses			
.	.			
.	.			
N	Setup savings			
N	Personnel savings / losses			
N	Other savings / losses			
			Total net present value:	

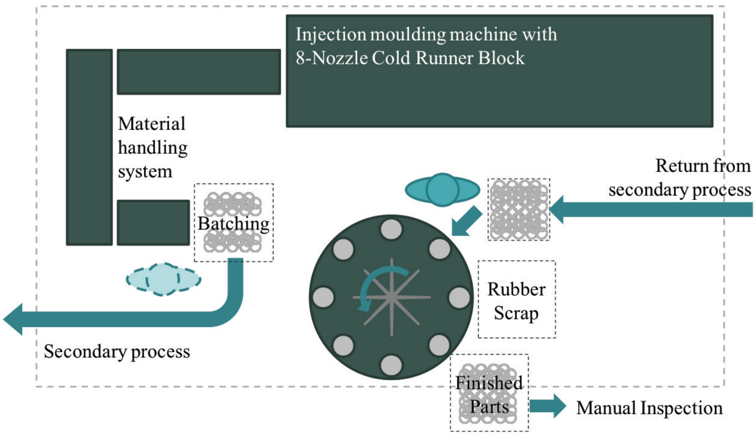

Fig. 1. The current production cell

3. Case study

3.1. Overview

The specific business unit of the company produces V-ring rubber seals ranging from 1.5mm to 450mm internal diameter. Product variety is hard; production of part numbers is done in batches before changing over to different part numbers. Production is typically characterized by short production runs (average of 2 to 3 shifts), thus performing frequent changeovers. Many standard catalogue items are currently manufactured using the “tube moulding and cutting” process, involving the injection or compression moulding of a rubber “tube” followed by grinding, cutting and dividing carried out on a dedicated cutting line. Currently there is a production cell which has become idle for 47 out of 52 weeks in a year. Thus there is an opportunity to develop this idle manufacturing system into a reconfigurable one which can produce parts currently produced using the tube-moulding process. The company wishes to convert this production cell to a closed cell which can be reconfigured to handle different products from the product family. The current layout of the cell, which can cater for two almost identical part numbers, is shown in Fig. 1.

3.2. Conversion

This procedure involved the systematic application of the guidelines listed in section 2, and is summarized here. With respect to the requirements of the RMS (Step 1), discussions were held with key stakeholders including the product manager representing product design and marketing, the production manager and the tooling manager. The first exercise involved redefining the product family, to find common key characteristics which can be exploited when modifying the manufacturing system. It was also recognized that a new approach was needed to keep the parts within the manufacturing cell and promote one piece flow rather than batching. The project would have to return a positive NPV by the end of its useful life, and to produce better quality parts thus at a lower scrap rate than the current method. To minimize impact due to machine downtime during the conversion process, the estimated (low) volumes produced by the current system for the next year would be manufactured before starting the project.

Inhibitions to the reconfigurability of the current system were identified, and a function – means analysis was used to draw up alternatives for the proposed system. This is shown in Fig. 2, and for each function the best solution was selected using a weighted ranking method. A similar exercise was carried out for each individual machine in the system, resulting in a number of critical design changes to achieve reconfigurability.

3.3. Economic analysis

A detailed economic analysis of the conversion revealed that this would result in a substantial positive NPV over the minimum expected useful life (taken to be five years) of the manufacturing system. This was fueled mainly by the cost of replacing worn out tools on the current system, which would be mandated if the status quo is retained at a cost that would exceed the capital outlay for the conversion process excluding engineering design and installation costs. In addition, the analysis revealed that the proposed system would greatly reduce the setup time per batch (by a factor of eight), and that the scrap rate would be reduced by a factor of three due to an improved cutting process. Furthermore, the potential of enhanced reconfigurability of the new mould tools using standard inserts; and of labour savings due to the use of an automatic injection moulding machine, further enhanced the viability of the conversion.

It is noted that the company’s policy mandates that the salary costs of resident engineers and technicians involved in the design and installation of a project should not be considered as capital expenses. This policy serves to drive innovation and process improvement by keeping the total project costs down. It is also noted that the production time lost during the conversion process would not affect the business since the current year’s demand on the manufacturing line would be produced prior to the start of the conversion process.

3.4. Evaluation

The proposed system design was evaluated with respect to the six characteristics of RMS, and found to satisfy all of these adequately. With respect to diagnosability, the system still makes use of the human element for identifying and characterising types of defects: however, it uses an expert system to diagnose the problem and provide suggestions for remedial action, and employs machine vision to measure the critical dimensions, giving the machine setter immediate feedback if dimensions are out of specification. With respect to scalability, the injection moulding output can be doubled with minimal investment; and beyond that with moderate investment in a larger cold runner block and mould tool. Additional system components can be added independently to incrementally increase capacity without major capital expenditure.

4. Conclusion

The guidelines were found to be very useful during the design process for conversion of the manufacturing system. The case study chosen for this project can be considered to be medium complexity since the process is short and the part family is made up of very similar parts. Thus further research is still needed to evaluate the extent to which the guidelines remain valid and straightforward in the case of more complex requirements. In the selected case study, the list of questions to be considered during the early stages of the reconfiguration process was updated

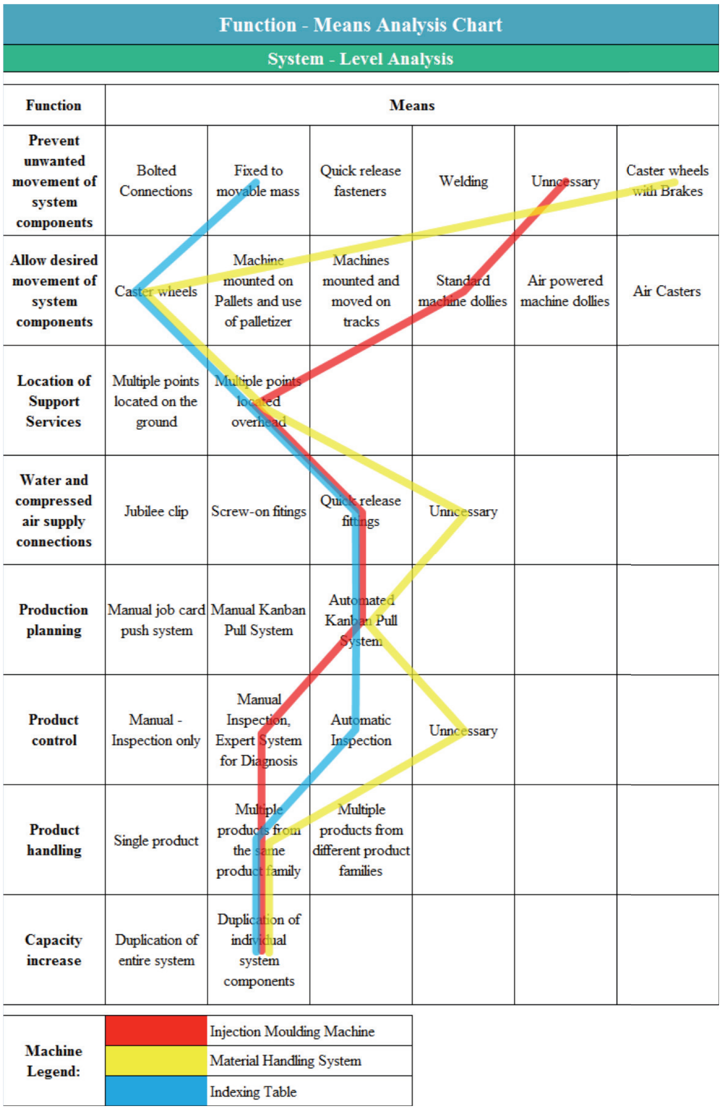

Fig. 2. Function – means analysis chart applied to the manufacturing system

following the first application of the guidelines. This indicates that some of the specific questions to be asked may vary according to the case under consideration. The exercise however clearly indicates that RMS may be economically feasible even if they are developed through the modification of a dedicated system.

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