Towards practical guidelines for conversion from fixed to reconfigurable manufacturing automation systems

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Abstract

It is generally considered that economic feasibility of a reconfigurable manufacturing system 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 perception, 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. It is shown that under certain conditions, reconfigurable manufacturing systems may be economically feasible even if they are developed through the modification of pre-existing dedicated systems.

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 the early 20th century (e.g. Bhuiyan and Baghel, 2005). 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. Buzacott, 1982). 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,

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and to be able to respond to customer requirements faster and more effectively (Koren *et al.*, 1999).

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 (Koren *et al.*, 1999). 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 (Mehrabi *et al.*, 2000). Mehrabi *et al.* 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 (Koren and Ulsoy, 1997). 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 (Mehrabi *et al.*, 2000; ElMaraghy, 2005).

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 (ElMaraghy, 2005). 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 (ElMaraghy, 2005); Wiendahl *et al.*, 2007. The study of reconfigurability in manufacturing extends to new approaches for control (e.g. Priego *et al.*, 2015 and Durkop *et al.*, 2014) and strategy (e.g. Fasth-Berglund and Stahre, 2013).

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 (Mehrabi *et al.*, 2000; ElMaraghy, 2005). 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 of RMS

The design of RMS needs to address both system-level issues as well as machine-level issues (Koren and Ulsoy, 1997). System-level design looks at the manufacturing system as a whole, composed of a number of machines as constituents of the system. Machine-level design focuses on the individual machines which make up that manufacturing system as seen in Fig. 1. 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.

2.2. A generic fixed manufacturing automation system

A generic manufacturing automation system in use at Trelleborg Malta is considered, in order to highlight the general limitations of fixed systems with respect to reconfigurability. The system being used for this example is an end-of-line inspection machine which was custom built for a particular product. Such systems are typically made-up of a number of cameras located around a rotating glass table. Finished parts are placed inside the bowl feeder which orients the parts and carries the parts to the feed track as seen in Fig. 2. The parts exit the feed track onto the glass plate where they are checked by a number of cameras. These machines are custom designed for specific parts; with just the number of cameras needed to inspect critical areas and dimensions of these parts according to customer and internal requirements.

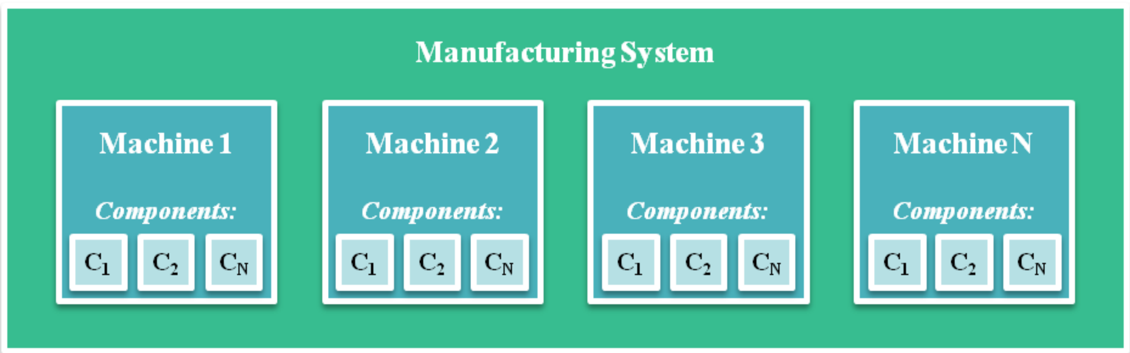

Fig. 1. System and machine level constituents of a RMS

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.

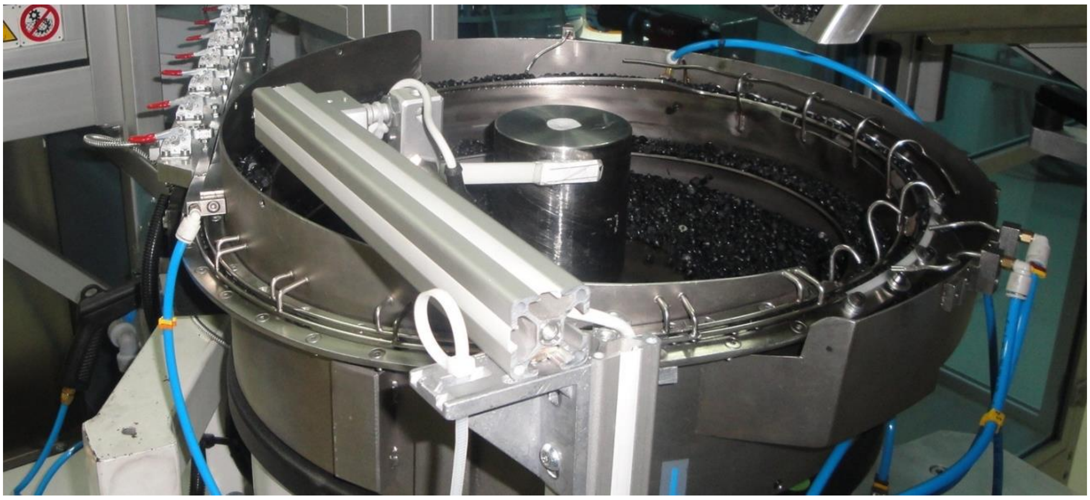

Fig. 2. Bowl feeder which feeds parts into the feed track

In this example, the system uses compressed air jets to orient the parts in the bowl feeder and to remove defective parts and good parts from the glass table, see Fig. 3. If a part with the same shape but different material, density or tribological properties needs to be used on this machine, then the air pressure would need to be adjusted. This would technically be possible; however this process is long and tedious and often takes weeks for ramp-up due to feeding problems.

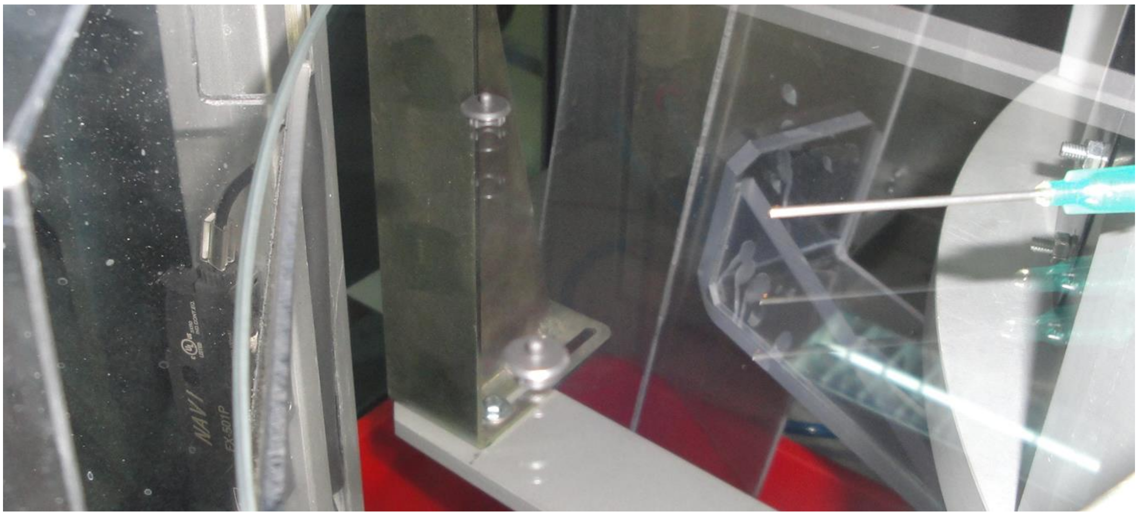

Fig. 3. Air jet needle on the right of the image, used for removal of parts from the glass plate

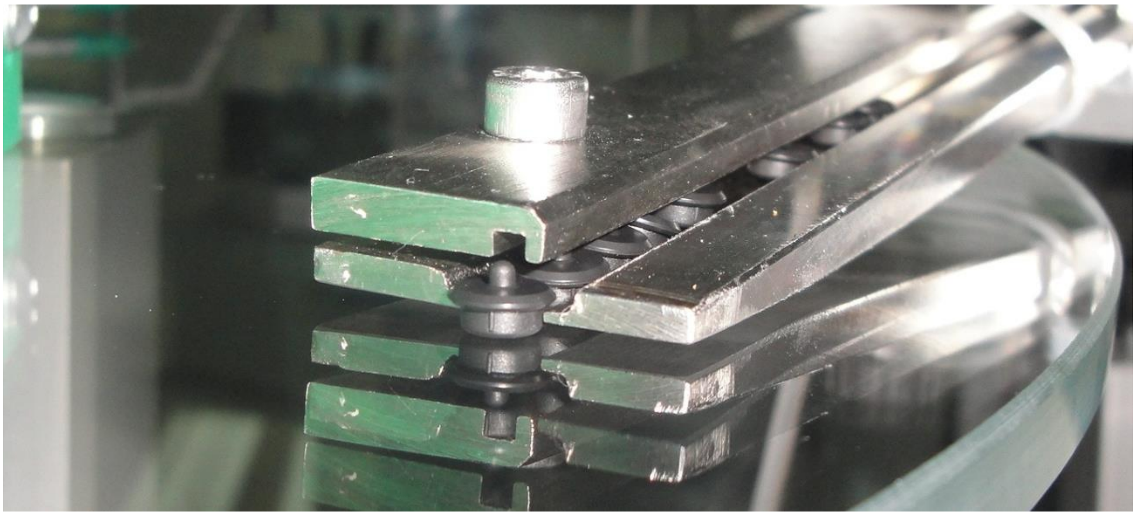

Fig. 4. Profile of part in feed track

Some features of the part can be modified without affecting the process; however the main shape of the part cannot be modified because it must compatible with the guide rails in the vibratory bowl feeder for orienting the parts. Also, a similar part with different dimensions would typically not pass through the feed track, (see Fig. 4). Thus systems of this type are typically not adaptable to different parts within the product family.

The system was designed for inspection of matt black parts. If the surface finish of the parts is different; it may cause issues for the cameras to identify defects. Furthermore, light coloured parts cannot be inspected on the current machine because the current lighting setup and transparent glass table make it difficult to contrast between a light coloured part and a bright background.

The system is currently made up of two cameras which inspect the top and bottom faces of the part while another camera is used to measure two critical dimensions of the part. The machine does not allow the addition of another camera; for example a camera to inspect the side of the part.

The inspection machines are currently running at maximum capacity in order to keep up with the demand. If the required volume increases, the system cannot be modified to be able to process more parts; thus requiring a large investment in a new machine. Furthermore, if one of the machine components fails, the entire system will stop until the problem is rectified.

The system software, as with many fixed systems, is locked by the machine builder and cannot be reprogrammed. For example, the production data is displayed in number format. It is not possible to display the production data in graphical format without going to the machine builder. Also debugging of software has to be done by the machine builder. The graphical user interface is fixed and cannot be modified to improve user friendliness for example.

2.3. Typical shortcomings of fixed automation systems

The typical shortcomings of fixed systems with respect to reconfigurability involve the inability to meet the requirements listed in Table 1, and in practical terms based on the generic system described in section 2.2 may 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.

2.4. 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 number of questions to be considered during the early stages of the reconfiguration process have been gathered from the literature search, particularly from Reza Abdi and Labib (2003), Koren and Shpitalni (2010); and Azab *et al.* (2013). 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 2.5 and 2.6 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.

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

<u>System components such as machines, material handling systems etc. cannot be added or removed.</u> 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 (Benjafaar *et al.*, 2002).

(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.

<u>Production planning and product routing between different system components cannot be changed.</u>

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.

<u>Parts being produced in the system are inspected off-line and poor quality production is not immediately detected.</u>

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.

<u>The current system can only handle one part number, and changeover to other parts is lengthy and complicated.</u>

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.

2.6. 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.

2.7. Flow chart of conversion guidelines

The flow chart given in Fig. 5 depicts the decision making process for whether or not to convert the current fixed system to a reconfigurable manufacturing system. It asks the critical questions which would be necessary to kick off such a conversion project. The flow chart does not consider the economic viability of the project because at this point, the cost of conversion would still be unknown. Fig. 5 links with the chart depicting the conversion process, given in Fig. 6.

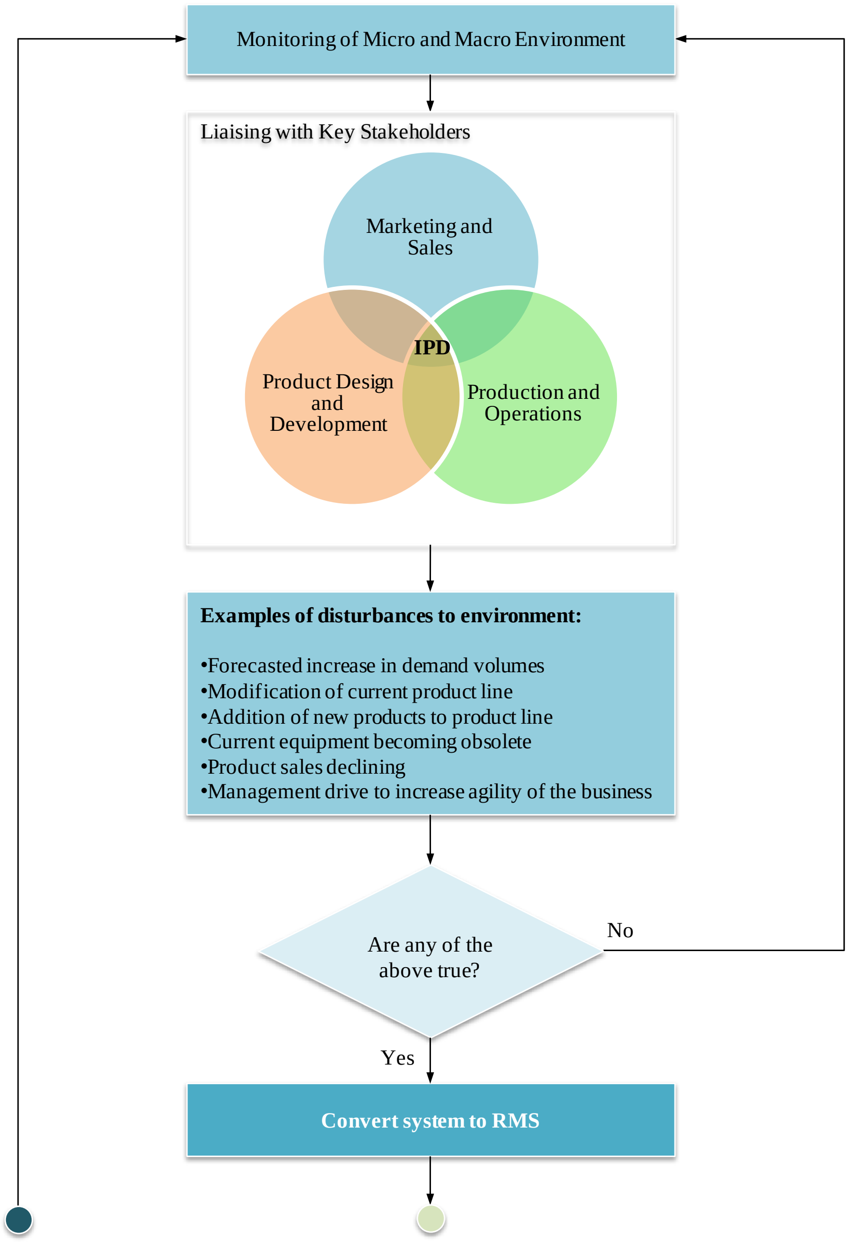

Fig. 5. Flow Chart depicting the decision process (Note: IPD indicates integrated product development)

Each decision box checks if one of the key characteristics of reconfigurability is present in the current system. If this is not present, the user is asked whether this requirement is critical for the manufacturing system to be able to achieve the requirements highlighted in the first flow chart. If this is not necessary, then the user can move to the next decision box. The decision boxes are located one after another to provide a structure which ensures that each of the questions are considered before having reached the end of the flow chart. It is noted that the flow chart in

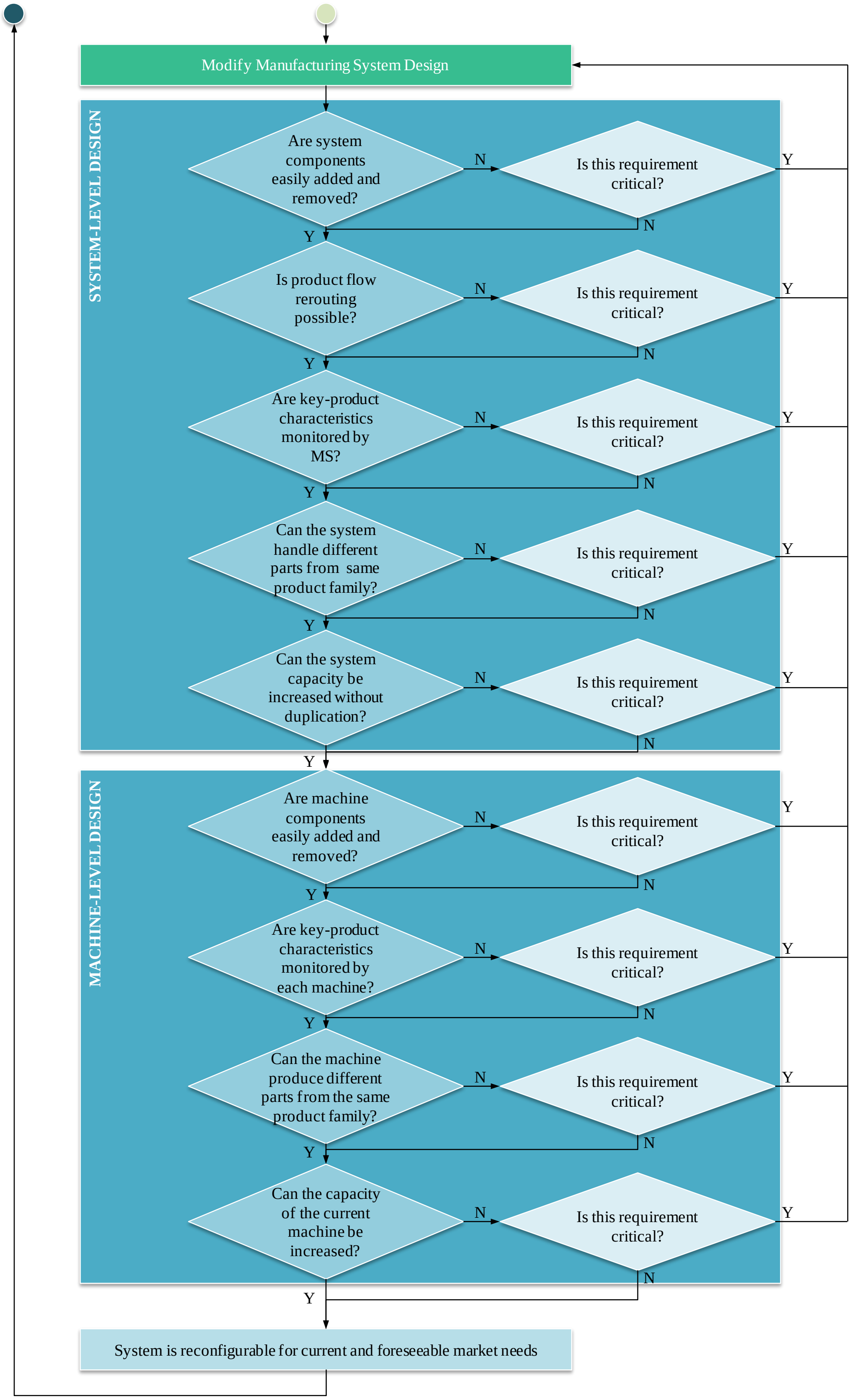

Fig. 6. Flow Chart depicting the conversion process

Fig. 5 addresses both the system and machine levels. While in some cases it may be sufficient to address only one of these levels, the flow chart as presented ensures that all opportunities for change are considered, and that the user follows a structure which ensures that all the steps are addressed accordingly.

Once the bottom of the second flow chart is reached and system reconfigurability is achieved, the flow chart loops back to the first stage of the first flowchart which is to monitor micro and macro environment. This loop is very important for the success of the reconfigured system and the business as a whole. Firstly, the manufacturing system may need to be modified at some point in the future, thus monitoring of market conditions is of critical importance. Furthermore, a business that constantly monitors (and reacts accordingly) to changing environmental conditions is far more likely to succeed than one which is oblivious to the internal and external environment.

The flow charts should be used in conjunction with the full conversion guidelines, since the latter give more detail in each stage. Similar to typical design processes, the RMS conversion design process is an iterative process.

2.8. 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.

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:	

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. Russell *et al.*, 2002). 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.

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

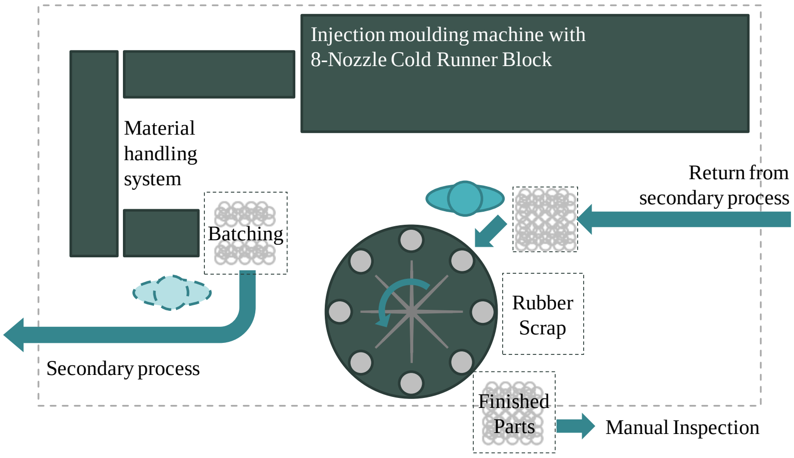

Fig. 7. The current production cell

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. 7.

3.2. Conversion

This procedure involved the systematic application of the guidelines listed in section 2, and is summarized here.

3.2.1. Defining the requirements for the RMS

V-ring production volumes are typically low. Thus to maximize the operational efficiency of the manufacturing system, it must be capable of handling different products from the same product family. Discussions were held with key stakeholders including the product manager representing product design and marketing, the production manager and the tooling manager. The first step was redefining the product family, i.e. what key characteristics are common and can these be exploited when modifying the manufacturing system. V-rings are mainly produced as standard items, and come in a variety of sizes, profiles and materials. Thus products with the same dimensions may be available in a different material and different section profile. Furthermore, production volumes vary greatly depending on the material and profile. Fig. 8 is a

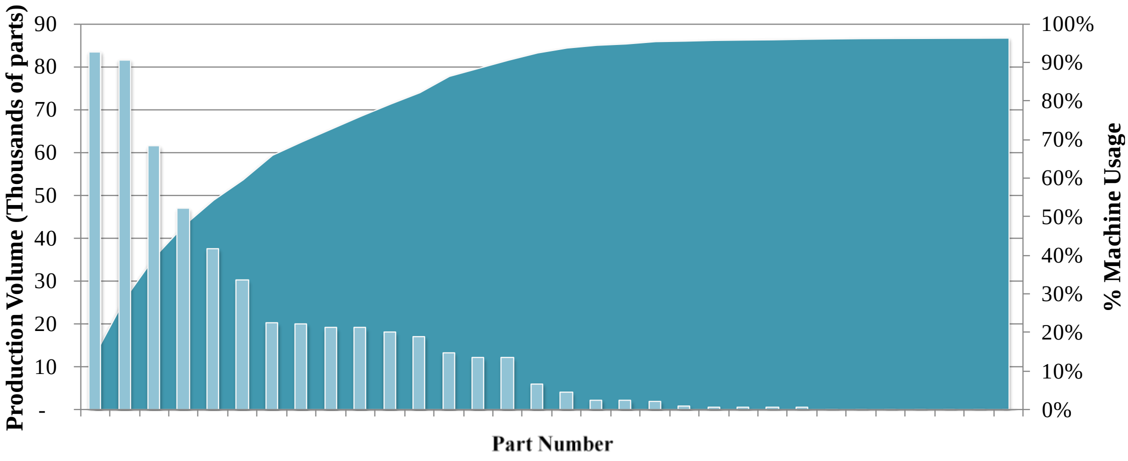

Fig. 8. Forecasted annual production volumes for the next financial year and the % cumulative machine usage for the proposed manufacturing system based on the selected production parameters

graphical representation depicting the cumulative machine usage of the part numbers chosen to run on the new system at the forecasted production volumes, including the part which is being produced on the current manufacturing system setup. Calculations are based on four parts per lift and consideration of different moulding cycle times which are dependent on the material. Production would span 7-hour shifts, 3 shifts per day, 5 days per week and 52 working weeks in a year. The machine usage plateaus at around 97% usage leaving an allowance of around 200 hours for changeovers and scheduled or unscheduled machine down time.

The current process also has a number of drawbacks due to the fact that parts are batched and taken for secondary processes between moulding and cutting. This increases the work-in-process and production lead times, which in turn reduces the response time from customer order to delivery. Also the secondary process used to remove flash from the parts is an expensive process which is prone to creating defective parts. A new approach must be created which will keep the parts within the manufacturing cell and promote one piece flow rather than batching.

The project has been assigned a cost of capital of 10%. The project must return a positive NPV by the end of the predicted useful life. Furthermore, the proposed process would need to produce better quality parts thus at a lower scrap rate than the current method for producing these parts. The current method has a global average scrap rate of around 30% while the part number produced on the current fixed system has an average scrap rate of 10%.

The current system was designed for medium volume production of two very similar products, specially designed for a customer. Orders for one of these products have stopped completely and the demand for the other product has reduced significantly. The manufacturing system is currently idle for 47 out of 52 weeks in a year. Given the very low operational efficiency of the current system; it is evident that this is a good opportunity to develop a new system. To minimize impact due to machine downtime during the conversion process, the estimated volumes for the next year will be manufactured before starting the project.

3.2.2. Address the current inhibitions to reconfigurability at the system level

A function – means analysis was used to analyze the current system and to draw up alternatives for the proposed manufacturing system. It was first analyzed at a broad, system level, thus looking at the machines or system components which make up the system. The manufacturing system is currently made up of three main components, these being the injection moulding machine, the material handling system, and the indexing table. Analysis was applied as per the guidelines given in sections 2.5 and 2.6 above, and the function – means analysis chart (Fig. 9) was used to help generate alternative solutions to the problem. Further details are given in the remainder of this subsection.

To prevent unwanted movement of system components, no changes are required for the injection moulding machine and for the material handling system. The indexing table (including the user interface and control unit) can be bolted to a metal platform to achieve reconfigurability while adhering to the manufacturer's recommendations for adequate anchoring. To *allow* desired movement of system components, movement of the injection moulding machine will be made possible through the use of standard machine dollies which will be permanently positioned under the machine. The two steering dollies will be located at opposite ends of the machine while the fixed skates will be located in the centre of the machine. Additionally a lockable safety brake will be welded to the machine structure to prevent unwanted movement of the machine during use. Movement of the material handling system and of the indexing table will be achieved through the use of newly installed castor wheels.

With respect to the location of support services, the manufacturing system already makes use of an elevated support service infrastructure, located three metres above the shop floor. The system is made up of a number of horizontal and vertical tracks passing through strategic points. Electricity, plumbing, compressed air or network connections can be made at any location within an hour. A vertical track will be made which will transfer the utilities down straight to the

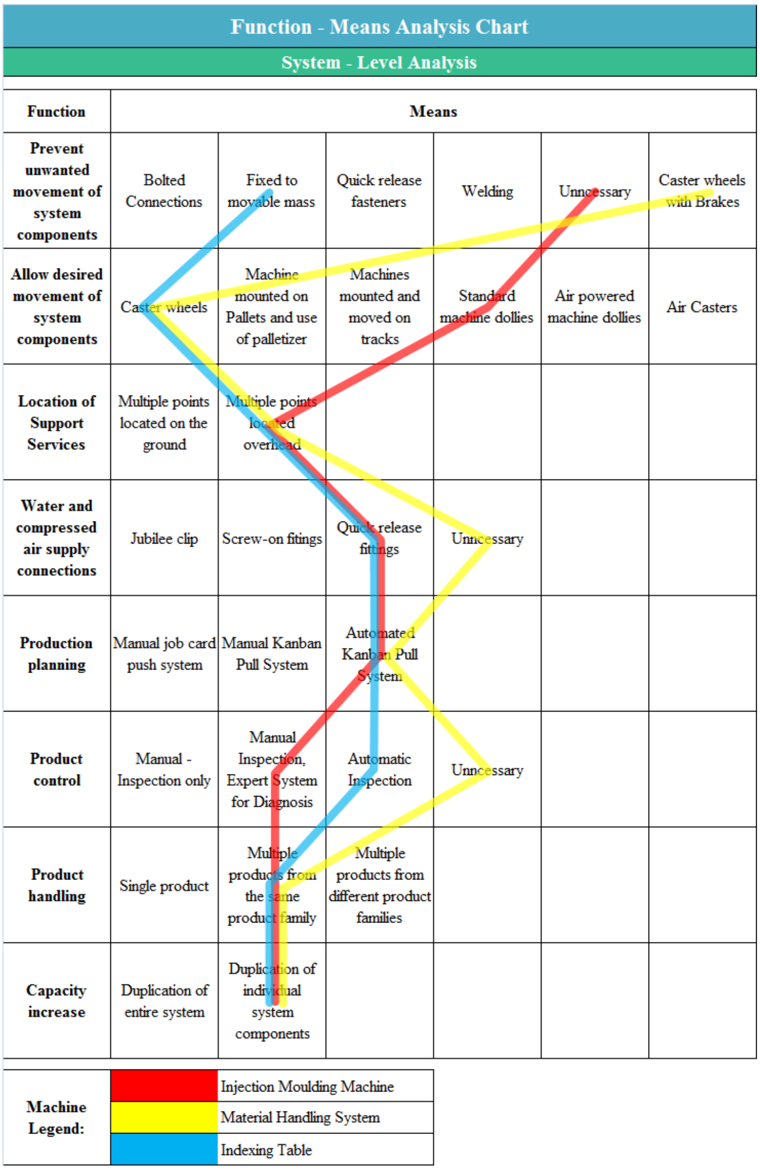

Fig. 9. Function – means analysis chart applied to the manufacturing system

machine. With respect to the supply of water and compressed air, quick connect coupling will be used for quick connection and disconnection of these services for the injection moulding machine and indexing table, while no modifications are required for the material handling system.

For production planning, an electronic Kanban system will be used, whereby when an order comes in for one of the products from the production line, the system will reserve parts from the finished goods supermarket. This will trigger re-stocking of the supermarket from the indexing table, which in turn will indicate that moulding of this part number needs to be started when possible.

With respect to product control, the injection moulding of elastomers is an exceedingly complex problem with product quality dependent on a very large number of factors including, but not limited to, issues related to raw material condition (e.g. humidity, particle contamination); machine parameters (e.g. mould temperature, cure time); tool condition (e.g. tool damage, tool wear); and other factors (e.g. nozzle seating, nozzle diameter). All of the above factors, and many others, will affect the final quality of the part. Unsurprisingly, some parameters have more of an effect on part quality than others. Some typical defects found during injection moulding of elastomers include blisters, flow marks, join marks, non-fill (short shot), excess flash (at parting line), dirty mould, cured-in rubber, foreign particle inclusion, undercure, overcur, dimensional error, tool damage, mismatch, and thick parting line. Thus, the automatic diagnosis and solving of moulding issues is extremely challenging. This aspect of the new design has therefore not yet been addressed, however it is envisaged that it would be possible to develop an expert system whereby artificial intelligence is used to help diagnose problems in the injection moulding process. With respect to the indexing table, one of the vacant steps in the indexing table will incorporate a camera to check the critical dimension.

With respect to product handling, the entire manufacturing system will be redesigned to be able to handle different parts from the same part family. With respect to capacity increase, the system will be redesigned so that if another injection moulding machine is added to the system, the parts from both machines can be handled at the same time without the need to reconfigure the material handling system. Both of these issues will be discussed further in section 3.2.3.

3.2.3. Address the current inhibitions to reconfigurability at the machine level

Problem A: Machine components are fixed and components cannot be added or removed.

Proposed solutions: All parts forecasted to be manufactured on the injection moulding machine do not necessitate any modifications to the machine setup but rather to the mould and cavity inserts. These are addressed under solutions to Problem C below. The material handling system consists of three conveyor belts which transfer the parts from the moulding machine into a box. Currently, parts are then transported to another department for cryogenic finishing and post curing. In the proposed system, the finishing process and post-curing process will be fully integrated into the manufacturing cell. To eliminate the need for cryogenic finishing, the indexing table needs be modified to allow the flash to be cut off during the cutting process. The system is currently made up of eight spindles which are attached to the indexing table using a collet chuck. This method of fastening spindles to the indexing table is quick and flexible for different sized spindle diameters and can be retained. Spindles for different product sizes will be manufactured.

Problem B: Parts being produced on the machine are inspected off-line and poor quality production is not quickly detected.

Proposed solutions: As discussed above, automatic diagnosability and automatic rectification of problems on the injection machine is not feasible at this point in time. An expert system can be developed whereby artificial intelligence is used to help diagnose the problem. With respect to the material handling system, inspection at this point would be useful for early detection of moulding issues. Also, at this stage the parts have lower value than at end of line since they have not gone through the entire process. Such a system would require orientation of the parts for the camera to inspect the critical surfaces. It is possible to carry out automatic orientation, inspection and transfer of parts onto the indexing table using a robot and machine vision system. On the indexing table, critical dimensions after cutting can be measured using machine vision with back lighting (see Fig. 10).

Problem C: The current machine can only handle one part number, and changeover to other parts (within the same part family) is lengthy and complicated.

Proposed solutions: The current setup is only capable of producing two almost identical part numbers. In order to be able to cater for a variety of part sizes; a bolster plate and insert cavity assembly was designed for the fixed, moving and floating middle plate; which would allow the system user to quickly changeover to a different part. Concept designs were discussed with key stakeholders including the product manager representing product

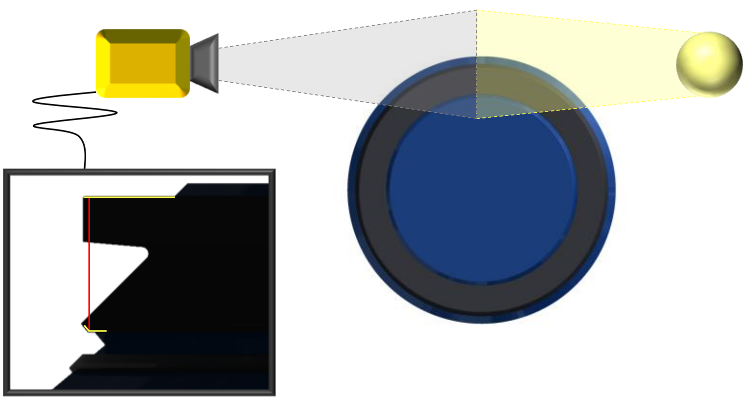

Fig. 10. Proposed inspection and illumination system

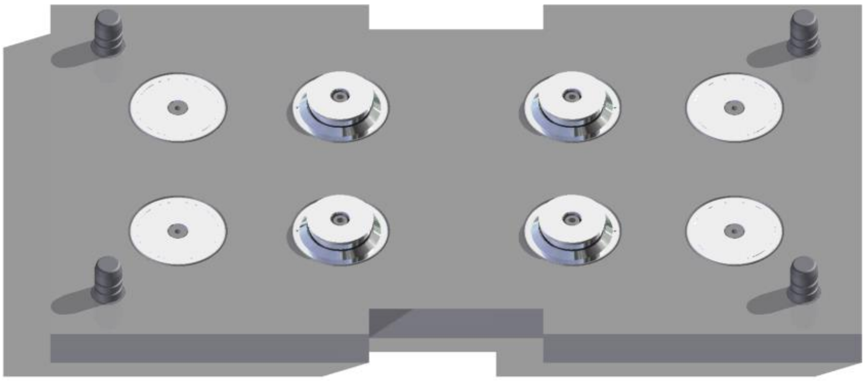

Fig. 11. Fixed plate assembly with four core inserts and four blocked inserts

design and marketing, the production manager representing operations and logistics and a representative from the tool room where the tool will be manufactured. All stake holders agreed with the concept of having mother moulds which remain permanently fixed in the machine; and interchangeable inserts. The material handling system, composed of three conveyor belts, can already handle all parts from the part family without the need to change over. On the indexing table, different sized parts would require setting of cutting blade positions relative to the part. Furthermore, future design changes may call for different angles and positions of the blades. The current system has manually adjustable slides which can be used to adjust position and angle of the blade and height adjuster for varying depth of cut. The same system will be replicated for the additional (third) cutting stage. In the future this can be automated to shorten the set-up times. Other parameters such as speeds and delays can be modified using the graphical user interface.

Problem D: Increasing capacity of current machine is not possible.

Proposed solutions: The design of the mould incorporates extra blocked inserts that can be utilized in case of a need to increase capacity (see Fig. 11). The machine is capable of coping with up to double the demand of all the part numbers from the product family. The material handling system is capable of coping with increased demand as long as the post cure oven is not over loaded. A detailed analysis was carried out to ensure that the oven can cope with increased demand. The indexing table can already handle more than four times the current demand.

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. Discussion

4.1. Application of guidelines

The guidelines were found to be very useful during the development of the manufacturing system. The case study chosen for this project would be considered to be medium complexity since the process is short and the part family is made up of very similar parts. Nevertheless, the guidelines were designed for a generic case and thus should not be affected by process complexity.

Before undertaking a project of this nature, the process designer should research the subject of reconfigurability and understand that it does not involve only modularity or scalability; but a different business approach which must incorporate all six pillars of reconfigurability both physically and logically. The ultimate goal of implementing a reconfigurable manufacturing system is to improve business agility and competitiveness. Once this is understood by the designer, stakeholder involvement is critical; from upper management-level, down to operator-level.

During the initial stages of the project, the requirements are often unclear and the future of the manufacturing system still unknown. For these reasons it is important to form a team which includes representatives from the major business areas. Here the scope of the conversion project must be made clear since some of the guidelines may not be applicable for the particular manufacturing process under consideration.

Furthermore, the list of questions to be considered during the early stages of the reconfiguration process was updated following the first application of the guidelines to the case study. Thus, with each application of the guidelines, there may be more questions to be added to the list, thus the current list is not an exhaustive one. As discussed previously, the aim of the list is to direct the thought process during the early discussions, thus providing a basis for defining the boundaries of the project and provoking discussion.

During the application of the guidelines a number of decisions needed to be taken. The importance of using decision making tools such as the weighted ranking method became evident in order to make good and unbiased decisions. Product development tools, such as morphological charts to generate alternative solutions to problems, and process failure mode and effects analysis (PFMEA) were applied, and these were found to be very useful.

It is understood that in most cases, the selected manufacturing system would already be several years old and also most likely have been idle for a while. An evaluation of the state of the machines should always be carried out before undertaking such a project to avoid unplanned repair costs and subsequent escalation of project costs. For the conversion project to be successful, it should be paired with a workspace optimization exercise (e.g. Abdulmalek and Rajgopal, 2007) and preventive maintenance on the entire manufacturing system to ensure maximum efficiency of the final system.

4.2. Validity of the results

When interpreting the results of any project, one must be cautious to ensure that subjectivity of the researchers carrying out the project does not influence the interpretation of the results. This project consisted of the creation of a set of guidelines, application of guidelines and evaluation of the results; all of which done by the same small team of researchers. While this may pose a risk of experimental bias, it is believed that an amount of subjectivity can be beneficial for research work due to the deep involvement of the researcher, who has a deeper understanding of the topic than outsiders (Ratner, 2002).

The interpretation of the results was done in a qualitative manner by analyzing the proposed system with respect to each requirement of reconfigurability. In this case, the conclusion is that the guidelines were found to be highly beneficial for the case study and that the proposed system exhibited all of the key characteristics which make up reconfigurable systems as described by Mehrabi *et al.*, (2000).

Useful future work would involve the development of a structured system for scoring the reconfigurability of any system, whereby a fixed system would be expected to rank low and a reconfigurable system to rank high. Other important future work would be to apply the guidelines to completely different systems, operating in different industries and applied by different people. In order for such an exercise to be successful, training of these persons would be necessary, which in itself may influence the objectivity of the exercise.

5. Conclusion

This work has provided a detailed and systematic approach for planning a conversion project along with practical examples of how such requirements can be achieved using current technologies available on the market. The guidelines are valid for the conversion of low to medium complexity manufacturing automation systems of this type. Further work is required to determine whether these remain as straightforward to apply to more complex manufacturing automation systems or if improvements are necessary. The work also makes use of discounted cash flow techniques for evaluation of the economic viability of such a conversion project. The exercise indicates that, contrary to the more common perception, RMS may under certain conditions be economically feasible even if they are developed through the modification of pre-existing dedicated systems.

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