Abstract: Change and uncertainty dominate today’s business environment. The competition is growing harder as the markets are becoming truly global. Customers are becoming more and more demanding, expecting to get product at the best price with immediate availability. Flexibility and low-cost manufacturing skills together with short delivering times are a necessity in order to meet with customer demands. The uncertainty in markets and the rapid introduction of new products has created a growing need for a flexible, reconfigurable and responsive manufacturing system. Thus, more and more companies, and especially small and medium sized enterprises (SMEs), are realizing that they have to make their production process more efficient or move their production abroad to countries with a lower labour cost. One way to improve a company’s efficiency and strengthen their competitiveness is to invest in automation. Industrial robots have extensively been developed over the last 10 years and their capacity and applicability has improved. However, robot automation investments are in many cases too difficult and too technically advanced for a SME. The objective of this paper is to investigate the need for flexible and reconfigurable robotic cells. The paper will first discuss some current manufacturing challenges and trends and will relate these to theories on flexibility and reconfigurability. Results from the Factory-in-a-Box project and the Robots to Thousands project will be presented and discussed in the context of flexibility and reconfigurability.

Keywords: Robotics, Automation, Reconfigurability, SME
1 Introduction

Today’s business environment is dominated by change and uncertainty, and global competition is diminishing defined markets. Manufacturing success and survival are becoming more difficult to sustain. It is recognized that low-cost and high quality alone are not enough to sustain companies' competitive position in market place. Meeting customer demands requires a high degree of flexibility, low-cost/low-volume manufacturing skills, and short delivery times. Success in manufacturing, and indeed survival, is increasingly difficult to ensure and it requires continuous development and improvement of how the products are produced. This highly competitive environment force companies to identify and develop unique manufacturing capabilities and to be innovative in producing and delivering products.

Thus, more and more companies, and especially small and medium sized enterprises (SME’s), are realizing that they have to make their production process more efficient or move their production abroad to countries with a lower labour cost. One way to improve a company’s efficiency and strengthen their competitiveness is to invest in flexible automation. Industrial robots have extensively been developed over the last 10 years and their capacity and flexibility has improved. However, it can still be hard for a SME to decide on an investment in robot automation. One reason is knowledge, small companies often lack the knowledge needed to realize the advantages of using robot automation or investing in the most advantageous robot solutions. This leads to situations when robot automation investments become too difficult and too technically advanced for the company.

Another reason for not investing in robot automation may be that the investment is hard to pay-off over the lifetime of a single product or project. The pay-off time of the investment have to be spread over several product generations which is often not technically possible due to inflexibility. The company cannot change the invested production system at the same rate as the product changes. If a change in the production system triggers new investments in engineering time from consultants or system integrators, the pay-off time of the system will be prolonged. This is a problem for especially a SME since they often lack specific automation competence needed to make the necessary changes in the automated production system, for example cost-effective changeovers between products and variants. Today, often half the cost of the investment in robot automation is the cost of engineering time.

This paper presents results from two empirical studies; one from the Factory-in-a-Box (Jackson and Zaman, 2006) project and one from the results of the Robots to Thousands (RTT) project within the Robot Valley program in Sweden. The results of the RTT project show the necessity for robot cells that have an increased level of flexibility and reconfigurability. A new type of robot cells should be developed that is both flexible and easy to reconfigure, enabling SME’s to handle changeovers without hiring experts. This kind of robotic systems would give an SME the confidence to purchase equipment that the company will be able to change accordingly as changes are introduced in the product or production process. The results from the Factory-in-a-Box project propose techniques for making robot automation more available for the companies in need of robotics technology. Some
results from the Factory-in-a-Box project will be presented in this paper and discussed related to the need for flexible and reconfigurable robotic systems.

2 Classification of Flexibility and Reconfigurability

Today, there are several different classifications and interpretations of flexibility used in the literature. The classification of flexibility and reconfigurability that is used in this paper is adapted from (Jackson 2000). These definitions suggest that flexibility has to do with changes due to changing circumstances. Flexibility of a manufacturing system can be defined and determined by its sensitivity to change (Chryssolouris, 1996). As changes can be of different time frames and different scope, it should be able to classify flexibility into different types. Slack (1987) found out through his study that four different types of flexibility was considered important by the companies that took part in the study: (1) produkt flexibility, (2) mix flexibility, (3) Volume flexibility, and (4) delivery flexibility. Another such classification is possible to do into eight different types (Browne et al., 1984):

- Machine flexibility – the ease of making changes in the machines required to produce a given set of parts.
- Process flexibility – the ability to produce a given set of parts, possibly using materials, in different ways.
- Product flexibility – the ability to produce different (set of) products.
- Routing flexibility – the ability to change routing, handle breakdowns, and to continue producing a specific part.
- Volume flexibility – the ability to economically vary production volumes.
- Expansion flexibility – the ability to expand the system easily and in a modular fashion.
- Operation flexibility – the ability to interchange the ordering of several operations for each part type.
- Production flexibility – all the part types that the manufacturing system can produce.

A flexible system is, using the definition in (Jackson 2000): a system that has been designed in accordance with the ability to deal with changes effectively. In other words, this definition of flexibility does not mean that development or change of the actual system is needed.

Thus based on this reasoning, flexibility is defined in this paper as the ability to robustly handle short-term changes quickly and at a low cost within an existing production system.

Reconfigurability on the other hand means the ability to adopt the production system rapidly in response to changing needs and opportunities. The earlier mentioned definitions of flexibility resemble reconfigurability in the sense of being able to handle changes in an existing production system. Reconfigurability differs by incorporating an aspect of uncertainty and unlimited scope into whatever changes need to be dealt with. Reconfigurability incorporates that the system can be deconstructed and reconstructed as needed.
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For example, a reconfiguration can be a change of capacity. Thus, reconfigurability and volume flexibility are closely related. Still, there can be various types of changes, besides changes in capacity, effecting a production system. Examples of this can be a change of a strategic supplier or a shift in a manufacturing technology. In the end, all these changes affect the capacity of the system and are thus included in capacity flexibility but these types of changes require development of the actual system and are therefore defined in this paper as a reconfiguration of the system. We need to be flexible to handle a large product scope; on the other hand we need to be able to reconfigure the system to both handle the old products as well as new ones.

ElMaraghy defines a reconfigurable manufacturing system (RMS) as a production system that promises customised flexibility on demand in a short time, in comparison to a flexible manufacturing system (FMS) that provides generalized flexibility designed for the anticipated variations and built-in a priori (ElMaraghy 2005). ElMaraghy also concludes that RMSs aims at (1) reducing lead time for launching new systems and reconfiguring existing systems, and (2) rapid manufacturing modification and quick integration of new technologies and/or new functions into existing systems using basic process modules that would be rearranged quickly and reliably (ElMaraghy 2005).

3 Flexibility and reconfigurability within robotics

When applying the classifications for flexibility and reconfigurability to robotics one realizes that a robot by itself is both very flexible and reconfigurable. They are flexible since they can be used for a variety of tasks and are able to work with many different types of products. An industrial robot is also reconfigurable by definition, the ISO definition for industrial robot specifies that it should be: automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes (Wikipedia 2006). Thus, the robot itself is both flexible and reconfigurable.

However, it is when the robot is placed into a workstation or cell that it becomes more rigid and inflexible. Most robotics installations of today are made in a rather stiff and inflexible ways that makes it difficult to implement changes and reconfigure the robotic system to meet with changes in the product or manufacturing process. Canny and Goldberg (1994) concludes that rapid reconfigurability will be critical for the manufacturing systems and that it can be supported through workcells that are “easily edited”.

The robots of today often have a longer lifetime than the projects or products that they are purchased for (Brunn 1996). This means that it is important that the equipment is reused over several projects or products. One problem with reusing the robot over several products is that a lot of smaller companies lack the knowledge to reconfigure and reprogram the robot for its new tasks. This means that the company has to hire consultants to reconfigure the robotic working cell

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This calls for more reconfigurable robotic working cells that are easier to reconfigure for new tasks.

Euron states in their report that flexibility and agility is becoming increasingly important for advanced production systems, as an alternative to efficiency that has been the main priority before (Euron 2005). This is because of the change in market where the customer will demand highly diversified product mixes in shorter delivery times, in smaller batches. This poses great demands in the production system in terms of the reusability and flexibility of the system (Euron 2005).

Standardization is one of the enablers that can be used to make robotics more available for the SMEs. The development of more standardized components, both hardware and software, can be used to implement more reconfigurable robotic workstations. Being able to change between different components easily without making changes in interfaces and control-software enables rapid changeovers and gives the opportunity to implement changes at less expense. The need for standardization is stated in both the Euron research roadmap (Euron 2005) and in the report from Teknisk Framsyn (Teknisk Framsyn 2003).

4 Programming and configuring industrial robots

One important part of the reconfiguration of robotic working cells is the programming of the behaviour of the equipments in the cell. ElMaraghy describes in (ElMaraghy 2005) that hardware reconfigurations also requires major changes in the software used to control the equipment in the cell. There are a lot of different types of equipment that needs to be controlled and thus programmed, for example: the robot(s), I/O controlled fixtures or transport systems such as conveyor belts.

There is a plurality of ways to program this kind of equipments. The robotic systems often have a vendor-specific programming language that is used to control the robot movements and in some cases other peripherals such as grippers and fixtures. In many installations Programmable Logical Controllers (PLCs) are used to control the behaviour of the robotic working cell. In the cases where PLCs are used they often control the equipment around the robot and the sequence of operations that takes place in the cell. Another way of controlling the behaviour of the robotic working cell is to use a PC-software running on a PC connected to the robotic system and other equipment. This PC solution is often referred to as Cell-PC and is often used if a graphical user interface (GUI) is requested for the application.

Many of the PLC or Cell-PC systems are programmed in a rather static way. This means that in order to implement a change in production, the user has to be a skilled programmer. This is one of the obstacles that the SME has to face when a change in a product or production line is to be realized and one of the reasons that they have to hire consultants in order to implement the changes.

There is a lot of research being conducted in the area of robot programming. The programming environments are becoming more visual and intuitive using graphical user interfaces and graphical representations such as the unified modelling language (Bruccoleri 2007). Bruccoleri also describes some of the differences between using a PLC and implementing PC-software to control the robotic working station. Bruccoleri concludes in (Bruccoleri 2007) that the
advantages of using PC-software over a PLC programming environment include the possibility to reconfigure the behaviour of the cell. It also provides other important functional requirements such as, but not limited to, real-time visualization/monitoring, networking integration and easy testing (Bruccoleri 2007).

The next step in programming robots are most probably going to include more intelligence in the programming environment. Biggs et al. propose that the productivity of the programming of robots will increase when the programming systems gets more intelligent, leaving the programmer to do less work while achieving the same results (Biggs et al., 2003). Also the Euron research roadmap concludes that man-machine-interaction is an important research topic within the robotics community (Euron 2006). New innovative ways of programming robot movement and interaction with its environment is an important field of research. Euron (2006) also identifies that learning and self-optimization of the robot programs through artificial intelligence is one of the six technical fields identified as important for the future. However, the Euron research roadmap points out that the lack of established standards in production robotics inhibits the development of intelligent and integrated automated manufacturing platforms (Euron 2005).

5 Empirical study 1 - The situation for SMEs

Small and medium sized enterprises have a hard time competing on a increasingly global market. Traditionally, companies competed on smaller markets where geographical position and closeness to the customer was important competitive advantages. This was especially true to the SMEs that often act as sub-suppliers to larger companies. However, today the trend has changed and made it more and more important for companies to differentiate themselves from their competition on other basis. Price per unit has become more important since new IT-structures and logistics make it possible for the buying companies to order manufactured articles from all over the world.

The need for production systems that are flexible and reconfigurable is also found in the report written by the program Teknisk Framsyn in Sweden, as they listed five key-areas that they conclude will be important while developing the production systems of the future; one of the areas is that “the customer wants to be able to chose customized products” (Teknisk Framsyn 2003, p. 4). The same report also describes the importance of mass customization and standardization in order to achieve that key-area. The same conclusions are drawn in the report “Visionary Manufacturing Challenges for 2020” established by the National research Council’s Board on Manufacturing and Engineering Design in the USA (National Research Council 1998). An article in (Magazine 1990) states that diversity is becoming more and more important to attract costumers. Products must be adopted to fit the specific needs of different costumers which makes manufacturing flexibility and the ability to produce non-standardized products a competitive advantage (Magazine 1990).

This new market environment has placed new demands on the SMEs that require them to change their production systems or products to make them more competitive. Companies have started to focus more on efficiency and how to lower their production costs. One way to make production more efficient is to remove the
bottleneck in the production line. A survey of 44 different studies conducted at different SMEs in Sweden shows that many of the bottlenecks within SMEs often originate from work stations that includes heavy-lifting or repetitive operations that are inefficient for humans to do. The studies have been made as a part of the Robots to Thousands (RTT) project within the Robot Valley program (RobotValley 2006). The companies that have been studied are SMEs and are located in the geographical area of Mälardalen in Sweden. The pre-studies have been conducted on a delimited part of the companies manufacturing system that has been considered to be a problem area at the company. The reason for doing the pre-studies was to see if robot automation may be used to rationalize or to increase the efficiency of the given section of the production system. The survey of 44 of the pre-studies made during 2004 and 2005 concludes that the main reasons for the companies to conduct this kind of pre-study are to:

- remove ergonomically bad workstations,
- get higher efficiency in workstation,
- lay off employees from workstations, and
- get higher utilization from equipment within workstation

Even though ergonomics has ended up as the one most common official reason for wanting to introduce automation into the production system, pay-off and higher efficiency has been shown to be the decisive factor in most cases when it comes to actually make an investment.

The survey also shows that the main application investigated for usage of automation was machine tending with almost 50% of the studies.

One of the main obstacles for the SMEs when investing in robot automation is the size of the investment. The pay-off time of the investment is often rather long and hard to calculate beforehand. The reason for this is that many of the SMEs have rather short horizons when it comes to product lifetimes. Many of the companies are sub-suppliers that only get smaller batch orders from other companies. Although the total amount of articles of a certain type can be rather large, it is often divided into several smaller orders, making it more difficult to predict the total number of articles that will be produced. The survey shows that about 45% of the pre-studies have rather long pay-off times, this even since the operation that has been studied has been chosen as having potential by the project management or company itself.

6 Empirical study 2 – Research results

Two projects have been carried out where the research team has been actively involved in the development and installation of two prototype robotic working cells. The cells has been created as an answer to the call for robotic working cells that match the requirements of SME’s in need of robot technology. The first installation was called Floating Storage and was the solution to a logistics problem at the industrial partner and was installed into production in 2004 (Hedelind et.al., 2006). The main purpose of this project was to find a flexible solution for assembling parts into a cabinet. The solution presented was implemented into a prototype and installed into a production line. The system consisted of two
industrial robots and several peripheral equipments that were controlled by I/O. Special designed software was implemented that controlled the behaviour of the cell and managed the buffer storage system. This solution has proven flexible in handling the wide variety of components that should be assembled and also handle changes in the design of the components. This flexibility is due to a vision system used and the configuration functionalities implemented into the Floating Storage software. However, greater difficulties can be seen when changing the overall logical programming of the robotic working cell. This is due to the fact that the logical behaviour is programmed in the PC-software and compiled into a machine code executable. This means that the person that are to change the logical behaviour of the cell has to be a programmer with knowledge in the programming language used (Microsoft .net C#), which is not true for the common operator working on the factory floor.

A second research project called Factory-in-a-Box was conducted with the same industrial partner as in the Floating Storage application. In this project more focus was on the reconfigurability aspects of the robotic working cell. A survey of the market of available PC-software that could meet the requirements of the industrial application was conducted, but no suitable solution was found. The decision was made to create new software that could meet with the industrial needs, which lead to that a new PC-software was designed and implemented as a prototype, called the Cell Configurator. This software supported the reconfiguration of the program-logic in the working cell with a more easy-to-use “drag-and-drop” programming style. This robot working cell consists of two robots cooperating together with other I/O controlled equipment such as a gluing station and a folding station. The programming of the logical sequences of the cell has been implemented as graphical user interface enabling the user to program the logical sequences in the programs as icon-based flowcharts. This type of graphical programming has been shown to be more visual to the user and more intuitive to use. The programming of the robotic movement paths has been implemented using simulation tools and some online programming. This installation was put into production at the industrial partner during the autumn of 2006.

The key-features of the Cell Configurator are flexibility, reconfigurability and generality. Flexibility because the software may be used for several different robot applications, enabling the user to have the same software solution and user interface on all its robot installations. Reconfigurability is implemented as it lets the user change the program-logic of the cell in a swift and intuitive way. Generality is implemented as a set of plug-in interfaces, allowing the user to create its own components and import them into the software. This allows the user to use any peripheral equipment that can be used programmatically and also to use any type of robot controller as long as its resources may be accessed from the PC.

For both these development projects the requirements included that the robot cell should be able to handle all the available variants of the product and also all future, not yet designed, variants of the product. This was enabled through developing and deploying software and hardware that was designed to handle the product variants and also was flexible enough to handle future changes, within a given span. The need of cooperation between the development team creating the production system and the product development team was identified. A close relationship resulted in that the product development team could set the correct requirements on the production equipment, and at the same time they learned what
type of changes they could introduce in the future. This cooperation leads to a much closer relationship that all parties benefited from in the long run.

7 Conclusions

Reconfigurability has been, and will continue to be an important feature of a manufacturing system, and thus also an important feature of each individual cell in the manufacturing system. As the production system is designed to become more and more reconfigurable, each working cell has to become more reconfigurable, this is especially true if the working cell is very capital intense. Generally when a company is investing in expensive equipment, creating a more capital intense production processes, the resource flexibility is becoming lower making it harder and more expensive to implement changes. This calls for new and more sophisticated techniques that enable the creation of manufacturing systems that are more rapidly changeable and can be reconfigured as the product or production requirements change.

In this paper, and the studies that preceded the paper, the need for reconfigurable robotics systems has been identified as an enabler for SMEs to rationalize and make their production more efficient. The need for introducing robot automation into SMEs has been identified in the RTT project. Also the need for more reconfigurable robotics systems has been identified as many of the companies that has been pre-studied in the RTT project has been unable to reach a good solution because of the long pay-off times or lack of knowledge within the area of robotics.

The topic of reconfiguration was investigated within the Factory-in-a-Box project and a software called the Cell Configurator was developed as a prototype to demonstrate the opportunities of graphical programming environments and highlight the lack of such software in the market today. The project identified two main areas that have to be improved if the need for reconfigurable robotic systems should be met: (1) more reconfigurable and intuitive software solutions, and (2) more standardization within both hardware and software.

Another important enabler that has been identified is the need for closeness between developing products and developing the production system or implement changes in the two. This has been an important topic for quite some time, ever since the introduction of concurrent engineering and integrated product development, but the need becomes even greater if some of the research or development is made by persons outside the organization, such as consultants or academic partners. This is an important lesson that has to be learned for all cooperation between the academia and the industry. Another similar conclusion from the Factory-in-a-Box project is that there is a great need for projects where academia and industrial partners meet and work closely together, since such projects can deliver much more applicable and useful results for both the academic and the industrial partner.

The final conclusion of this paper is that in order to install and use robot automation in a production system, the company should have an automation strategy. This has been shown in the RTT project where several pre-studies have been conducted on present robot solutions in order to make them more efficient. Also, as a result of the Factory-in-a-Box project and the Floating Storage project,
the industrial partner in those projects has realized that it is necessary to have a strategy for what to automate and why. This has lead to a new project where the need for automation strategies will be investigated and a proposal for a model for automation strategies will be developed. This is future work for the research group that will be conducted during the upcoming years.

8 References


