Proceedings of DET2011
7th International Conference on Digital Enterprise Technology
Athens, Greece
28-30 September 2011

AGILE MANUFACTURING SYSTEMS WITH FLEXIBLE ASSEMBLY PROCESSES

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ABSTRACT

Traditionally automated manufacturing required high volume and large batches. New technologies for flexible assembly lower the volume requirements and increase the possibilities for product variation. The effectiveness of flexible assembly does however put new demands, but also opens new opportunities, to the manufacturing organisation, the manufacturing logistics chain and the control of material flow. This paper describes two case studies in two Norwegian manufacturing companies. One is a furniture manufacturer for the consumer market; the other is an automotive 1st tier supplier. Both are faced with increasing customisation of products with increased variations and decreased volumes of each individual product. The focus of the research is how the manufacturing organisation and the internal material flow need to adapt to gain from the investment in the flexible automation solutions.

KEYWORDS

Agile Manufacturing, Flexible Assembly, Manufacturing Organisation

1. INTRODUCTION

The concept of Agile manufacturing is still being refined by the research community, but according to Oleson (1998) agility is understood as "the ability to respond effectively to unexpected or rapidly changing events". Wiendahl et al (2007) defines Agile manufacturing as "the strategic ability of an entire company to open up new markets, to develop the requisite products and services, and to build up necessary manufacturing capacity". Yusuf et al (1999) compiled a list of "main points in the definitions of agile manufacturing" where high quality and highly customised products with high information and value adding content, responsiveness to change and uncertainty, social and environmental issues and synthesis of diverse technologies are some of the topics on the list.

An agile manufacturing system must be able to quickly respond to the changes and the assembly process is often used as an enabler to create mass customised products, and is a key process for many companies to achieve agility. The aim is typically to co-locate the main T-point and the decoupling point intermediate store. Components are typically purchased or manufactured to an intermediate stock by using Just-in-Time/pull principles. The finished product is assembled to order to deliver the diversity the customer requires.

To achieve the required flexibility in assembly the assembly process is often realised by utilising manual labour, but demands to improve efficiency and quality leads companies to find automated solutions or combinations of manual and automation (Consigilo et al, 2007, Krüger et al, 2009). Conventional automated assembly systems do not handle frequent change, unpredictable events, and disturbances.

During the last two decades, however, novel concepts for highly flexible and reconfigurable assembly cells have been proposed and realised in research labs. Concepts such as plug and produce (Arai et al, 2000) leads to increased flexibility and reconfigurability, but few of these have been commercialised and made available as standardised systems on the shop floor.

A reason why these novel concepts have not been implemented in a larger scale might be that it is difficult to standardise assembly operations, so even though standardised assembly components exists, like vision systems and robots, the complete assembly cell will be specialised and complex. Specialised complex equipment will always have a high entry barrier for use, a large investment cost, and it will often take a long time before a manufacturing organisation can utilise the potential.

This requires a focus on how to create user-friendly systems. A car is for example a highly complex device, but the user interface is extremely simple. ~~Better understanding of complex equipment can also be supported by improving feedback and adding learning abilities.~~

Even if a technological solution has been found for an assembly challenge, the resulting system must fit into the total manufacturing system. Requirements for operator presence and internal material flow must be fulfilled, and the manufacturing organisation must be able to utilise the potential of the automated assembly system and work around the limitations. Even if modern assembly technologies are very advanced, it will never have all the capabilities of a human operator, but it will also have other qualities which the human is incapable of.

The missing link between advanced assembly technology and successful industrial implementation is tools to improve the interaction between the operator and the equipment, tools to assess the right level of automation and how to make the automated solution fit into the manufacturing organisation, and tools to help manufacturing organisations utilise the potential of advanced assembly technology.

This paper presents a case study of two manufacturing companies who have introduced flexible and reconfigurable assembly systems which will completely replace manual operations.

The paper is sectioned into three parts. The first part of the paper will give a short introduction to the state-of-the-art in assembly technology. The second part will present the two case studies with their current manufacturing system and challenges, and the assembly system which is proposed. Section three will sum up the results from the case study and present important factors to consider when implementing flexible assembly systems, and propose areas for further research to make current technology more available for industrial use.

2. RESEARCH FOCUS AND METHODOLOGY

This paper is a case study of two mass producing companies which deliver mass customised products. Another part of the research project has examined the core assembly processes, and proposed, tested, and developed prototypes to prove that it is possible to automate these. The research in this paper focuses on how these solutions can be implemented in these companies manufacturing systems and production processes.

The information for the study has been collected by following the research on the new automated assembly systems, and interviewing people at various levels in the manufacturing organisations.

Introducing complex technology to a manufacturing organisation will always fail if the organisation is not prepared, the technology does not live up to expectations, and there is no user-friendliness.

3. STATE-OF-THE-ART IN FLEXIBLE ASSEMBLY TECHNOLOGY

Design and implementation of assembly systems has evolved through half a century and has been influenced by a lot of different research areas. Especially the automotive industry has pushed flexibility and adaptivity for automated assembly solutions (Michalos et al, 2010). Key challenges has been approached from a variety of angles, and not least is there no common agreement on which implementation approach is the correct to fulfil the dream of an assembly system with human like flexibility and machine like dexterity and accuracy.

The central component of a flexible assembly system is the industrial robot. Industrial robots are continuously improved with technology like automated calibration (Arai et al, 2002), improved absolute accuracy (Watanabe et al, 2005), and lightweight design with intrinsic safety and similarities to humans (Albu-Schäffer et al, 2007) with kinematic redundancy, compliancy, and two-armed setups.

Grippers are another central component which is under heavy development. Most gripping principles have been developed, like contact, needle, vacuum, etc., but flexibility of grippers is still in development. Grippers resembling human hands (Butterfass et al, 2001) with several degrees of freedom and integrated sensors are available, but still have a premium price tag.

Sensors are the key element for assembly systems to interact with their surroundings. Sensors are essential for part recognition, part joining, and quality control. The most common sensors resemble human capabilities, like vision, contact, and force and torque sensors (Santochi and Dini, 1998).

A robot equipped with grippers and sensors is capable of executing assembly tasks; the missing piece of physical hardware is the feeder. The most common feeder principles are vibratory bowl feeders, elevator feeders, belt feeders, and drum feeders (Boothroyd, 2005). Flexible feeders which present parts on a flat surface using vision sensors for part location have become common and are commercialised (Zenger et al, 1984). These feeders use common feed principles like belts, flipping, and vibration to move and reorder parts. Another approach under heavy research is bin picking, where the feeder is skipped, and the robot picks parts directly from a bin (Kristensen et al, 2001).

By themselves these physical components are not capable of doing anything. The must be taught and controlled.

To perform a task a robot needs to do movements and interact with the environment. For assembly robots the interaction is mostly gripping, and the movements can be for transport or guiding. The main part of a robot program can be created offline on a computer, and simulated to check for functionality or it can be created online in an assembly system. Offline capabilities have been available for several years, but lack in accurately representing the real world, so often online adjustments are needed. To improve online capabilities modern robots can be equipped with force feedback systems which makes it simpler for operators to physically move the robot through required trajectories (Pires et al, 2009), or vision systems which makes it possible to learn trajectories by “watching” an operator (Fujita, 1988).

Robots can also be used in cooperation with operators, either by assisting them by doing heavy lifting or in cooperation where a robot does some parts of an assembly, and the operator the rest (Krüger et al, 2006).

All components in an assembly cell must be controlled. Current research focuses on distribution of control. By distributing control only parts of an assembly system will be affected by minor changes. Holonic Manufacturing Systems is the common term for distributed systems, which is the software side of creating Plug and Produce assembly systems (Arai et al, 2000).

To increase quality and robustness, and improve operator understanding of complex assembly systems, feedback and monitoring systems are crucial. Both short term information to understand the current status of an assembly system, and long term information to use for improvement analysis must be available.

By distributing control and integrating closed loop feedback and monitoring systems in assembly systems, autonomy and self-X capabilities can be introduced. X can be capabilities like calibration, adjustment, optimisation, etc. (Scholz-Reiter and Freitag, 2007).

The technology for creating advanced and complex assembly systems is available. The task is to find the correct technology which creates a feasible system, at the correct cost, and with the required capability. It is not feasible to create a complete system at once; it has to be built up gradually to keep complexity and investments under control. This will be a long term iterative process, and it is important that the manufacturing organisation and strategy is committed for a long term.

4. CASE STUDIES

4.1. EKORNES

4.1.1 Case introduction

Ekornes is the largest furniture manufacturer in the Nordic region, with a vision to be one of the world's most attractive suppliers of ergonomically designed furniture for the home. Ekornes has almost all of its manufacturing operations in Norway. It is a very profitable company which has proved able to counter the operator costs in a high-cost country with technology development and automation, as well as premium prices based on very strong brands. The main products are high-quality reclining chairs and sofas of the Stressless® brand. All finished products are manufactured to customer orders.

A modular design of the recliners includes a very limited range of internal steel frames, foam-moulded cushions, and swivel bases. This has facilitated batch manufacturing of a number of parts and modules to stock. The manufacturing of the seating cover however, is not initialised until a customer order is placed. Due to the complexity of handling limp materials – in this case mostly furniture hide (soft leather) parts and some textile parts, the manufacturing of seating covers has been kept mostly manual. The seating cover lead time varies, but is typically below two weeks. New models (or changes) are introduced every year, and each seating cover consists of several (~20) parts which must be routed through manufacturing together.

A typical recliner consists of steel frames inside moulded foam plastic cushions for the seat and back body of the chair. Armrests and a typical accompanying footstool are similar, but have simpler frames. All these main modules have covers for surface finish and seating comfort. The cover modules are frequently layered with one or more fibre layers attached to them. The swivel base is typically of laminated wood, and some high-end models even have leather covers and steel parts on the base. An essential seating comfort feature is the possibility to adjust the seat, back, and headrest position.

4.1.2 Current manufacturing operation

The process to create a seating cover is first to cut hide and fibre to create the core parts of the cover. The cutting of hide is performed on manually operated punching machines, or in digital cutters. The quality inspection of the hide, and the manual or digital placement of the cover parts – while still maximising hide utilisation – is a vital element in the quality of the finished product. The fibre is then attached to the hide parts on traditional industrial sewing machines. Some parts are sewn in special sewing machines with a gathering seam, in order to improve fit of the seating cover to the chair. These subassemblies are then sewn together in several steps to create a complete seating cover. This also includes some parts of fabric (typically a technical textile). In the final assembly process, the seating covers are drawn over the cushions and chair frame.

The cover is the part of the chair with the highest product variety. Thus, the process times and process complexity vary a lot. The overall planning of the factory is based on running a certain number of standard seating units per day - across departments. In the cover manufacturing, this creates a need to schedule each day as a mixture of covers with short, standard and long process or cycle times, in order to achieve a fairly stable capacity factor. A large variation in process complexity and cycle times is traditionally an argument in favour of manual and thus flexible operations. However, Ekornes also utilises a piece-rate remuneration system for its operators. This has undisputedly contributed to industry leading and increasing productivity. On the other hand, this stimulates a certain specialisation among the operators. They will naturally perform better on operations they know well, and will try to compose small batches wherever possible. This tendency towards operator specialisation also supports the need to have a general mixture of cover models each day. Even though the overall principle in the cover production is one-piece flow based on customer orders, the general production pattern is typically 2-5 covers for the same chair model grouped together in one production order. It should be noted that customers – furniture dealers – often place orders for more than one chair of the same kind. The technology in the sewing department also drives process specialisation to a certain extent. Some of the cover making sewing processes requires special sewing machines with features such as gathering seam.

4.1.3 Current product flow

The production flow in the cover making process for recliners in the main factory may be described as follows: Parts for a given production order (one or a few covers of the same model) are punched in the manual punching machines or cut in the digital cutters. The parts are then manually loaded into trolleys – one for each production order – that are moved around the sewing department on an overhead conveyor.

The sewing department is all on one floor, and seemingly one large department. It consists however, of a number of sub-stations and sub-departments. The trolleys are first directed to sub-stations performing so-called pre-sewing operations. The typical example is the attachment of fibre to the cover hide parts, often combined with a gathering seam. The cover parts are manually lifted out of the trolley, and sewn together with more standardised material, like fibre parts, that are picked from buffer stocks at the sub-station. Finished sub-assemblies are then put back in the trolley. The trolley is then directed to the sub-department for the actual model range. There are approximately 10 such “mini sewing departments”, each containing 20-25 manually operated sewing machines, and typically handling 2-3 cover models. The cover parts and sub-assemblies are again lifted out of the trolley, and the sewing operations constituting the major share of the sewing process time, are then performed by a sewing operator. The finished covers are put back in the trolley, which moves over to the assembly department. Here the covers are unloaded and reloaded on one-piece flow trolleys together with the other parts and modules for the chair, and moved to finishing assembly.

A typical process time for the sewing of a complete cover is less than one hour, but the throughput time in the sewing department is typically 2-4 days. The work-in-process buffer stocks are in front of the sub-stations and sub-departments. This enables the production managers and organisers to balance the department load by mixing orders with short and long process times, as well as providing the operators an opportunity to pick production orders that suit their competencies, and preferably form batches.

The core assembly process in the production of seating covers is the sewing. Sewing is important to create the right quality and look and feel of the chair. Other processes have been tested, but sewing provides the best quality and is viewed vital for customer satisfaction.

4.1.4 Proposed flexible assembly solution

Why then is the sewing automated? Why is a hybrid cell where the operator sews and part transport is automated not sufficient? At Ekornes, the argument is manual process time, and as mentioned earlier the major share of the time in the sewing process is at the sewing machine. Through automating steel and wood part manufacturing, painting, foam moulding, and other standardised components manufacturing, total manual process time for a typical recliner has been reduced from 5 to less than 3 hours. Sewing operations however, still accounts for close to 1 hour, as it did 20 years ago. The target of the automated sewing project at Ekornes is to reduce manual sewing time by 50%. This will be achieved through automating the sewing processes best suited for automation. The first automated sewing processes are based on special machines sewing special, fairly standardised cover parts. The automated sewing cell discussed below is much more flexible, and performs the fibre attachment to different cover hide parts, also including gathering seam. Gathering seam requires a special sewing machine, and the material cannot be fixated when fed through the sewing machine.

The automated sewing cell consists of a robot, a sewing machine, several sensors, and control units. Each physical unit contains its own controller to simplify exchange, and to prepare for future sensor development. The sensors are essential to make automated sewing possible. Two or more components are stacked together, and the robot guides them through the sewing machine. Because of sharp corners, the sewing process is not necessarily continuous for one component, and because of complex shapes, one component might be relocated and regripped. This setup will behave similar to how an operator handles the process, and has been deemed the only viable process to handle the variation of parts and the gathering seam.

Since the components which are to be sewn are limp or non-rigid, there are several sensors which supervise the process which is then continuously adjusted. The sensors are responsible for detecting how the components are located, how they move through the sewing process, and to detect whether the sewing operation progress.

Before the sewing process begins, the different components must be located, stacked and transported to an initial position where the assembly cell can pick up the stack and move it to the sewing machine. The components vary in size – dimensions from 10 centimetres up to 1 metre – and shape – width / height ratio from 1:1 to 1:10, and variations of circularity –. By designing a flexible gripping system, a limited set of tools can handle all parts. By including a tool change system, one assembly cell can handle all variants.

The system includes monitoring of all critical input and output parameters to improve feedback, and to improve understanding of how the assembly system works. Monitoring information will also be available for long term analysis. As mentioned earlier, the sewing process must handle limp materials and it is not feasible to fixate the parts. This results in a process which is not repeatable, thus the need for continuous sensor supervision and process regulation. The operator – which is close to the process – must be able to understand and tune the process. In a variable process like sewing, it is the experience of the operator which creates optimal process parameters.

As the process is not repeatable, it is impossible to handle all problems which may occur. As the furniture hide is visible to the customer, it is crucial that the process does not create any visible features on any hide. If a piece of hide is damaged, it is a time consuming operation to replace it, as it must fit in colour and finish with the other pieces for a chair. So it is preferred to stop the sewing process early, and hand the part to an operator for repair.

It is important with tools to improve the process, but with the described assembly task, teaching of new products will be as crucial. There are a lot of factors which are important to create a routine to sew one part. Sewing speed, where to gather, how much to gather, curvature, entry and exit point on the part, entry and exit at the sewing machine, etc. Some of these factors can be planned ahead, but most must be defined by experienced personnel. The proposed solution to create a program is to draw a path on picture of the part, and then split the path into segments. Different factors for each segment can then be set. The operator can then adjust all these based on visual and sensor feedback to create and optimal process.

4.1.5 Integration of assembly in manufacturing organisation

The theoretical performance of the proposed assembly system makes it a feasible solution. The initial investment of a robot, a sewing machine, cameras, sensors, and grippers is relatively small. It is also possible to extend the automatic material flow chain, to increase operation time without human interaction.

In theory one sewing cell can process all different components, as the sewing principle is equal. In practice this is not feasible, as this increases the need for equipment like grippers and feeders.

To handle the total production volume, several sewing cells will be needed. Since the principle for all cells will be equal, it will be simple to move products, programs, grippers etc. between cells. So even though some specialisation will be needed for one cell, the cells will be more flexible than operators because their specialisation can change. Factors like variation in part size, sewing time etc. will affect whether a cell might specialise in one part, or maybe handle all parts for a complete chair. Another important factor will be how components for one chair can be routed through manufacturing as fast as possible, and without losing track of the components which belong together.

As the current sewing operations have little automation, it is important not to create a system which is too large and complex. The operators need to be gradually introduced to the automated processes. The proposed flexible assembly solution handles a certain degree of variation, but as how to handle a part to produce the correct seam is workmanship, teaching and adjustment of the sewing parameters must be made available to the operators. Precise and consistent feedback is also needed to make operators understand how different actions affect the process.

By keeping some material handling operations manual, the operators will be kept busy, and the total complexity of the system will be reduced because the processes will be decoupled. A buffer will be located at each sewing cell, so one operator can handle several sewing cells, and can work asynchronously.

Depending on the level of automation, the operator can do stacking and feed each component, feed a stack of components, or fill a feeding device. Traditional feeders do not work well with limp materials, so some preparation must be done before a handling robot can take over. Stacks are relatively stable and can be transported on conveyors. The cycle time for sewing one part ranges from 10 seconds to one minute, so handling will not be a bottleneck.

As mentioned earlier it is difficult to create a process without errors, so a repair operation is needed. As the products are made to order, the repair has to be done in connection to the process, the parts for repair cannot be stored and fixed in batches.

4.2. KONGSBERG AUTOMOTIVE

4.2.1 Case introduction

Kongsberg Automotive (KA) is a worldwide 1st tier supplier for the automotive industry. Their product line includes systems for seat comfort, clutch actuation, cable actuation, gear shifters, transmission control systems, stabilizing rods, couplings, electronic engine controls, speciality hoses, tubes and fittings. The case product line in this paper is couplings. Almost all coupling manufacturing operations is located in Norway, and has been able to counter the operator costs by focusing on high technology products and automated manufacturing.

The primary marked for couplings is air brake systems for commercial vehicles. Couplings are designed for a variety of tube dimensions, with a variety of interfaces and interface dimensions. Currently the programme consists of 100-150 unique variants. The product specific volume range is from ~10,000 to ~4,000,000, so most products are manufactured to stock.

To increase KA's share of the value chain for air brake systems, they have introduced complete manifolds with fitted couplings, which reduce their customers' requirement for assembly. Manifolds consist of a housing plate and a set of couplings. The product specific volume for each manifold will be much lower than the component volumes, so most manifolds must be made to order.

Since air brakes are a safety critical system in a commercial vehicle, there are not often large product changes. But small continuous changes to improve product performance, both for functionality and internal processes occur.

A new product programme was introduced some years ago, where one innovative product was a coupling with a washer based port side. This coupling can be mounted into a port by pressing, whilst traditionally couplings had to be screwed. This simplifies assembly, and creates new possibilities for manifold design and assembly.

By utilising the washer based coupling, no taps are needed in the ports of the manifold house, so the housing plates can be created by injection moulding. By designing injection moulding tools with inserts – and combined with the large variety of couplings – it is possible to create an endless variety of products.

4.2.2 Current manufacturing operation

Today couplings are produced in high speed dedicated manufacturing lines. Most components for the couplings are made in-house from composite granulate and extruded brass rods. Because of short cycle times – below 2 seconds – and small product size – from 5 to 50 millimetres – components are places in large bins. Components are feed into in specialised high speed automated assembly cells by a mixture of dedicated and flexible feeders and placed in boxes or blisters.

With a yearly volume of ~100 million couplings, this is the sensible solution. The initial volume for manifolds is estimated at some hundred thousand. Because of the large theoretical variety of assemblies, and the relatively low total and product specific volume, a different solution had to be developed for the assembly of manifolds.

The current manual assembly of manifolds is relatively simple. One operator takes one manifold, the corresponding couplings, and a fixture and presses one coupling at a time into the manifold. All couplings must be checked for correct positioning, and the needed pressure force is so high that safety equipment is needed. This setup is duplicated to achieve the needed production volume.

As the assembly operations are relatively simple, the cycle time will be low. Since all ports on a manifold might be equal, but require different fittings, the probability of failure is quite large, especially as the volume for one specific assembly reaches one. These concerns are also a driving force behind choosing an automated solution.

4.2.3 Proposed flexible assembly solution

Why does the assembly operation need to be automated? At KA, the argument is short supply chains and high quality requirements. All components are produced at a production facility in Norway, utilising highly automated assembly lines. These provide high efficiency, high quality, and are the most profitable manufacturing solution. Manual assembly would be located in a low cost country, dividing manufacturing in distance and increase throughput time. As the air brake system is safety critical, product and process control is essential.

The core assembly process for assembly of one manifold is simple; it is the large variation of parameters which is the driving force behind a flexible assembly solution. And since the product specific volume is low, all variants has to be included in the assembly cell to create a large enough total volume.

The proposed automated solution consists of two robots, equipped with sensors, grippers and tool change system. One robot is responsible for picking couplings and placing them into the manifold. The other robot is responsible for picking the manifold, presenting it for coupling insertion, and holding the manifold in the press. No fixture is needed, as the robot can hold the part while pressing. The sensors are responsible for part location, support for part insertion, and process and quality control.

A two robot setup like this will behave like an operator which can simultaneously pick and press parts, so the potential for an efficient and profitable solution is present.

There are three main tasks which require flexibility: location and gripping of parts, joining of parts and feeding of parts. And as research has shown (Krüger et al, 2009), feeding and gripping can be the costly and time consuming part of an assembly system.

For flexible introduction of parts into the assembly cell, vision is chosen. By using vision for location of parts, parts can be introduced in a variety of ways without requirement of re-teaching locations. Parts can be introduced in kits, blister or flexible feeders, and it will not matter for the assembly process. It will only require parts in some allowed poses and within the field of vision.

To simplify gripping, and reduce the amount of flexibility needed, design for automated assembly has been utilised. The different couplings have similar features, with different sizes. The manifolds can be divided into similar groups which all receive features with equal position and size, unrelated to performance of the product. This limits the need for flexible grippers, and a set of grippers and a tool change system can handle the product variation.

Joining of the coupling and manifold is always done at the same position. This simplifies generation of trajectories, and improves the possibilities for optimisation. Theoretical positions for each joining operation can be found by extracting information from CAD's, but because of the inaccuracies in the robots position system, inaccuracies in gripping, and inaccuracies in the injection moulding process, inline optimisation of positions is required. To support this process, the robots are equipped with force sensors. The force sensors can be used to improve initial positions, and be used during operation to supervise whether the assembly operation was completed successfully. Due to demands for low cycle time – below 3 seconds for one pick and place cycle – there is no time for force controlled insertion.

One primary obstacle in using vision is the calibration between vision coordinates and robot coordinates. The cell can self-calibrate by using a rough digital cell description, known calibration objects, and force feedback.

To improve teaching time and performance of the vision system, couplings and manifold houses are designed with unique features. Also by utilising similar features of different components, vision analysis for location is shared by parameter sets.

Force feedback is also used to prevent collisions, which can occur if parts are picked incorrectly or other failure situations.

All sensor information is monitored and provided as feedback to the operators. This improves understanding, thus improves the ability for operators to tune and optimise the system. Often operators see that improvements can be made, but they do not understand why the assembly system acts as it does, and which parameters to change to improve the situation.

Since the brake system is a safety critical component, full traceability of all components is required, especially as the system will go through continuous changes for improvement.

4.2.4 Integration of assembly in manufacturing organisation

The theoretical performance of the proposed assembly system makes it a feasible solution. The initial investment of two robots, cameras, force sensors, and grippers is relatively small. It is also possible to extend the automatic material flow chain, to increase operation time without human interaction.

Some basic efficiency performance indicators have been proposed to make the total OEE acceptable: An introduction time of less than one hour for an unknown manifold, less than 15 minutes for unknown coupling, unmanned production for 8 hours, and zero defects. By utilising the flexible setup, the possibilities of offline programming of robots and vision, and the integrated sensors, this is within target.

The assembly process in itself is not very difficult, and the manufacturing organisation is used to handle automated manufacturing equipment. The key to achieve a successful implementation is that the operators can understand and improve the system continuously. Precise and consistent feedback is also needed to make operators understand how different actions affect the process and monitoring and traceability will secure the quality of the product.

Even though the system consists of a set of advanced technological solutions, the cell is still not as flexible as an operator. An operator can pick a set of components, a fixture and start assembling. By making it possible to feed parts into the assembly cell by different methods (kits, blisters, feeders) it is possible to introduce only the needed parts for current batch: kits for small batches, flexible feeding for larger batches.

By introducing sensors into the cell, the assembly operation will be continuously supervised. Data can be used for optimisations, both online and offline. A lot of information can be used to facilitate offline programming; preliminary vision analysis can be created with a set of pictures and a simulation.

By keeping some handling operations manual, operators are kept busy, and the assembly system can be decoupled from the rest of the manufacturing system.

4.3 Case conclusions

The main challenge of the automated solutions presented in the case studies is the need for flexibility. This results in an advanced automated solution, which again requires empowered operators. By utilising standard assembly equipment, focusing initially on the core assembly process and leaving some material handling tasks to the operator, the initial investments in the assembly cells have been kept low.

It is important to let the operator work asynchronous to the assembly cell, so that the operator has time to interact with the system to get a better understanding of the process. The monitoring and feedback system will also improve learning of the operator, and increase the possibilities for the operator to improve system performance.

By designing the assembly operation “fail safe” we will have no errors, but we need to “repair” products. This is still a better solution than all manual, and a situation which can be improved. Too often an “all or nothing” approach is used when automation is introduced.

The last crucial factor is the empowerment of the operator. The systems must be designed for continuous change. A continual presence of an operator with skills to change and improve the system is necessary, and tools for feedback and optimisation must be present.

5. KEY FACTORS

In this chapter, the authors try to list some of the key factors for a flexible automated assembly process. We have indentified 5 main factors, each with 5 sub-factors; Material flow, Human interaction, Technical solution, Economy and Changeability. Table 1 shows an overview of the main Key factors and the sub-factors. Table 2 suggest 3 levels. The key-factors are mutually dependent on each other directly or indirectly.

Table 1- Key factors

Material flow	Human interaction	Technical Solution	Efficiency	Changeability

Decoupling point	Man-machine cooperation	Self-X	Availability	Changeover-ability
Redundant paths vs. special	Feedback/ learning	Monitoring and control	Quality	Reconfigurability
Kit/batch/group	Competence	Autonomy	Initial investment	Plug and produce
Automated feeding	Maintenance/ support	Traceability	Variable costs	Ramp-up
Volume/product portfolio	Complexity	Standardisation of equipment	Cycle time	Offline capabilities

Table 2- Factor levels

Main elements	Sub-elements	Suggested levels		
		1	2	3
Material flow	Decupling point	Store (finished goods)	Before assembly	Components manufacturing
	Redundant paths vs. special	Full redundancy/ flexibility	Partial redundancy/ flexibility	Special machines
	Kit/ Batch/ group	One-piece flow	Grouping	Batch
	Automated Feeding	Manual	Asynchronised manual (conveyor, blister, etc.)	Automated (feeder, bin pick, etc.)
	Volume/product portfolio	Low volume, short product range	Low volume, medium product range	Medium volume, medium product range
Human interaction	Man-machine cooperation	Synchronised	Asynchronised	Fully automated
	Feedback/ learning	None	Monitoring	Monitoring and analysis
	Competence	Low	Medium	High
	Maintenance/ support	No support	Medium	Close contact/ instant
	Complexity	Simple	Medium	Advanced
Technical solution	Self -X	None	Some	Extensive
	Monitoring and control	None	Simple	Extensive
	Autonomy	None	Simple	Extensive
	Traceability	None	Date and time/ batch	Each individual and process
	Standardisation of equipment	Standard off-the-shelf	Medium	One-of-a-kind special purpose
Efficiency	Availability	50%	75%	80%
	Quality rate	90%	95%	100%
	Initial investment	Low	Medium	High
	Variable costs	Low	Medium	High
	Cycle time	High	Medium	Low
Changeability	Changeover-ability	High	Medium	Low
	Reconfigurability	High	Medium	Low
	Plug and produce	None	Some	Yes
	Ramp-up	Long time	Short time	Instant
	Offline capabilities	None	Some	Fully

5.1. MATERIAL FLOW

Material flow or manufacturing logistics is a key factor for the usefulness of an assembly solution. Within the Material flow we have identified 5 sub-factors: Location of the decoupling point, which is the place in the process chain where the product dedicated to a specific customer. A system based on "make to order" would probably need a more flexible solution than "make to stock". Moreover is the redundancy of the material flow, one-piece-flow vs. batch production, how components are transported and fed into the process as well as the product portfolio and volumes important factors within the material flow.

5.2. HUMAN INTERACTION

Human interaction is the second key factor with the following sub-factors: Man-machine cooperation, Feedback/learning, Competence, Maintenance/ support and Complexity. First, the factors cover to what degree manual labour is a part of the process; can the operator work asynchronous? What is the automation level? On the other hand, the factors cover how human knowledge is developed and used to achieve a good automation solution. To what degree is the operator getting feedback from the process trough sensors? Are there any monitoring and/or analytical / decision support systems? What is the competence level of the operators and technical staff on automation? Is the process dependent on outside support form a third party? How complex is the system?

5.3. TECHNICAL SOLUTION

Section 3 is giving a brief overview of state-of-the-art of technology for flexible and agile automation technology. More or less cognitive systems with a "Self-X" such as Self-Optimisation, Self-Calibration, Self-Adjustment, Self-Repair etc. are one important factor to reach agility. The monitoring and control mention at the human interaction is also dependent on the technical solution. The degree of autonomy (Scholz-Reiter and Freitag, 2007) is to what degree an assembly cell can control itself in a decentralised way. Traceability of components, products and process parameters is furthermore an important technological key factor for quality assurance, and process analysis and improvement.

5.4. EFFICIENCY

The OEE factors availability, quality and cycle time is in addition to variable costs and investment costs, the key factors regarding efficiency in this study.

5.5. CHANGEABILITY

The main factors for changeability are the changeover-ability between existing product portfolio. Other factors include reconfigurability when the system needs to change, Plug and produce facility as well as ramp-up period and capability for off-line programming and manufacturing of grippers and pallets.

6. CONCLUSIONS

Although the development of solutions for advanced automated assembly has come a long way during the last decades, there are still several tasks which manual operators still can do better than automated systems.

The research in this paper shows that it is possible to exchange specialised manual operations with automated processes if the surrounding manufacturing organisation is adapted to handle the new equipment, and the operators are empowered to transfer their skills to the automated system.

Technical solutions to handle advanced assembly tasks are available, but when combining these with advanced control structures, most operators will have problems understanding why the system responds as it does. And understanding is important to make operators and manufacturing operations interested in automated solutions. Improved solutions for feedback and learning in complex assembly systems are therefore needed, and should be a focus area in research.

7. ACKNOWLEDGMENTS

The authors are most grateful to Ekornes and Kongsberg Automotive for their support in this research project. We would also thank the Norwegian Research Council for funding the research by the BIA programme, and SFI NORMAN.

REFERENCES

Albu-Schäffer A., Haddadin S., Ott Ch., Stemmer A., Wimböck T. and Hirzinger G., "The DLR Lightweight Robot – Design and Control Concepts for Robots in Human Environments", Industrial Robot: An International Journal, Vol. 34, No. 5, 2007, pp 376-385

Arai T., Aiyama Y., Maeda Y., Sugi M. and Ota J., "Agile Assembly system by "Plug and Produce"", CIRP Annals – Manufacturing Technology, Vol. 49, No. 1, 2000, pp 1-4

Arai T., Maeda Y., Kikuchi H. and Sugi M., "Automated Calibration of Robot Coordinates for Reconfigurable Assembly Systems", CIRP Annals – Manufacturing Technology, Vol. 51, No. 1, 2002, pp 5-8

Boothroyd G., "Assembly Automation and Product Design", 2nd Edition, CRC Press, Boca Raton, 2005

Butterfass J., Grebenstein M., Liu H., Hirzinger G., "DLR-Hand II: next generation of a dextrous robot hand", Robotics and Automation. ICRA 2001. IEEE International Conference on, Vol. 1, No. 1, 2001, pp 109-114

Consiglio S., Seliger G. and Weinert N., "Development of Hybrid Assembly Workplaces", CIRP Annals – Manufacturing Technology, Vol. 56, No. 1, 2007, pp 37–40

Fujita N., "Assembly of Blocks by Autonomous Assembly Robot with Intelligence", CIRP Annals – Manufacturing Technology, Vol. 37, No. 1, pp 33-36

Kristensen S., Estable S., Kossow M. and Brösel R., "Bin-picking with a solid state range camera", Robotics and Autonomous Systems, Vol. 35, No. 3-4, 2001, pp 143-151

Krüger J., Bernhardt R., Surdilovic D. and Seliger G., "Intelligent Assist Systems for Flexible Assembly", CIRP Annals – Manufacturing Technology, Vol. 50, No. 1, 2006, pp 21-24

Krüger J., Lien T.K. and Verl A., "Cooperation of human man machines in assembly lines", CIRP Annals – Manufacturing Technology, Vol. 58, No. 2, 2009, pp 628-646

Michalos G., Makris S., Papakostas N., Mourtzis D. and G. Chryssolouris, "Automotive assembly technologies review: challenges and outlook for a flexible and adaptive approach", CIRP Journal of Manufacturing Science and Technology, Vol. 2, No. 2, 2010, pp 81-91

Oleson J.D., "Pathways to agility", 1st Edition, John Wiley & Sons Inc., New York, 1998

Pires J.N., Veiga G., Araújo R., "Programming-by-demonstration in the coworker scenario for SMEs", Industrial Robot: An International Journal, Vol. 36, No. 1, 2009, pp 73 - 83

Santochi M. and Dini G., "Sensor Technology in Assembly Systems", CIRP Annals – Manufacturing Technology, Vol. 47, No. 2, 1998, pp 503-524

Scholz-Reiter B. and Freitag M., „Autonomous Processes in Assembly Systems", CIRP Annals – Manufacturing Technology, Vol. 56, No. 2, 2007, pp 712-729

Watanabe A., Sakakibara S., Ban K., Yamada M., Shen G. and Arai T., "Autonomous Visual Measurement for Accurate Setting of Workpieces in Robotic Cells", CIRP Annals – Manufacturing Technology, Vol. 54, No. 1, 2005, pp 13-18

Wiendahl H.-P., ElMaraghy H.A., Nyhuis P., Zäh M.F., Wiendahl H.-H., Duffie N. and Brieke M., "Changeable Manufacturing – Classification, Design and Operation”, CIRP Annals – Manufacturing Technology, Vol. 56, No. 2, 2007, pp 783-809

Yusuf Y.Y., Sarhadi M. and Gunasekaran A., “Agile Manufacturing: The Drivers, concepts and attributes”, International Journal of Production Economics, Vol. 62, No. 1-2, 1999, pp 33-43

Zenger D., Dewhurst P. and Boothroyd G., “Automatic Handling of Parts for Robot Assembly”, CIRP Annals – Manufacturing Technology, Vol. 33, No. 1, 1984, pp 279-281