



Implementation of Flexible Automatic Assembly in Small companies

Flexibility and process demands

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-Flexibility and process demands

A Doctoral thesis

by

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"If all you have is a hammer, everything looks like a nail"

ABSTRACT

This thesis has its focus within Flexible Automatic Assembly (FAA) systems and its implementation in small companies. The small companies are an important part of a country's industry and economy. The need for the small company to increase the technology level, in order to be competitive in a global market as a supplier, is evident. The prevailing competence and economical resources of most small companies are often limited, a fact which underlines the need for economical, technological and application flexibility for their assembly system solutions. Therefore, these needs could be viewed as the main objectives posed on solutions which claim to be flexible, such as FAA systems.

The objectives for this thesis are:

- to investigate the state-of-the-art in FAA systems; the primary focus of the investigation residing upon flexibility issues. Theoretical study.
- to investigate the implementation process in a small company that tries to apply FAA technology, and observe the problems that must be solved. Empirical study.
- propose an approach as to how FAA systems should be structured.

As a prerequisite for the proposed structure, the state of the art within FAA systems is discussed with focus on flexibility. The work in this thesis is based on the hypothesis that if systems are developed with properties satisfying the SME needs, the FAA-systems would be user-friendlier both in an economical- and a competence perspective. Hence the need to evaluate the status of current FAA systems.

The work attempts to illustrate, through the theoretical and empirical studies, that there are three main factors that limit success when implementing FAA systems in small companies: Competence acquisition, Product design and Strategy for implementation. Learning, or competence acquisition, is most often carried out in parallel with the actual use of the system. This extensive learning phase most often leads to the system becoming obsolete during its expected run-time (period of use). The product design is another area of interest as it often seems hard to motivate product changes to facilitate automatic assembly, especially if no system is at hand as a driving force. The work also showed that there is a lack of strategy for implementation of FAA. The understanding of the FAA system impact on the product development and manufacturing is not understood, thus, the implementation is treated as a local phenomenon in the assembly shop. Furthermore, the

uncertainty concerning future development of products is reflected in short pay-off times, which makes the economical justification of systems difficult.

All of these factors have been misrepresented to date due to a loose application of the term flexibility, and its implications. Therefore, the work attempts to clarify the flexibility issues, in terms of the assembly process demands, and also proposes a new flexibility map.

To facilitate implementation of FAA into small companies, a modular assembly system approach is proposed. The modules should be task oriented. By using a modular approach, the possibility to have a system that is easy to keep up to date with product development, is greatly improved and the risk to invest in dead ends will decrease. Furthermore, it should become simpler to find an optimal level of automation or to prioritise the flexibility efforts, and thereby reduce the cost for maintaining flexibility over the system lifespan.

A way to develop a decision-making tool for prioritising the flexibility efforts is proposed by using a Penalty-of-Change curve, which exploits the proposed flexibility map as a base. The modular approach is a way to decrease the negative correlation between dynamic flexibility (on-line) and static flexibility (off-line), since too much dynamic flexibility otherwise tends to limit the possibility to change the system to new situations. The modular approach isolates this negative correlation within modules. The technological adaptability will increase if a modular system is used since the standardised interfaces between modules define clear borders between functions or tasks within a system. Furthermore, a modular approach facilitates stepwise knowledge acquisition since it will be natural to focus on modules instead of entire systems.

A leading idea in this thesis is, that small and large companies have the same system demands at module level, which makes it possible to increase the market for standardised modules and thereby decrease the cost for such modules. In other words, standardised modules, instead of systems. Modular systems are not optimised in terms of a low cost/capacity ratio for a certain product generation, instead, the system is optimised towards, reconfigurability to be able to follow product evolution, or totally rebuild for new products. Which, in the long run, may lead to a low cost/capacity ratio. Therefore, a prerequisite for the use of modular systems is that the systems will operate in a frequently changing market where fast ramp-up are more important (to maintain the market share) than an optimised system for each product generation.

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3. Byron Carlsson T, Eskilander S., Johansson R., Petersson P. " A structured set of concrete rules for design for automatic assembly", International Symposium on Automotive Technology and Automation, June 2-5, Dusseldorf Germany, 1998
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INTRODUCTION AND RESEARCH AREA

This chapter intends to describe the background and problem area. The last decade's need for changes in manufacturing strategies has affected the way products are developed and the way they are produced. This will be shortly discussed. The supplier's growing importance is further discussed and its consequence: The emerging need for small companies to increase their technology level in the assembly area.

This thesis has its focus in two areas:

- The small company and...
- The automation of assembly systems

The small companies are an important part of a countries industry and economy. The need for the small company to increase the technology level, in order to be competitive in a global market as a supplier, is evident [Bhattacharya et al., 1995]. The focus on automation of assembly systems is within the area of Flexible Automatic Assembly systems (FAA) and how to increase the use of these systems. The necessity to cope with the competition and to stay up to date with the technology development is a major reason for robot automation such as FAA [Mårtensson, 1995b]. However, the uses of these systems have not increased as anticipated [Tichem et al., 1999]. The small companies need to increase its technology level and the unsatisfactory low uses of FAA systems are the corner stones of this thesis. If FAA systems could be adjusted to the small company needs the market for FAA systems would increase significantly.

In the following sections the background will be detailed and, at the end of this chapter, there will be a description of the scope of this thesis.

1.1 Production¹ strategies are changing

The way in which the industrial world is producing its products has changed. The early 20th century's mass-production has evolved into a more customer-oriented production [Pine et al., 1993]. Other trends such as Information Technology have made it possible for companies to compete on markets world-wide [Freund et al., 1995].

¹ In this thesis "production" is used in the meaning of all the elements and functions that support manufacturing [Cochran, 1998].

In conjunction with this development, or perhaps because of it, the customer's preferences have changed. Only products or services that more or less exactly match the need of the customer are worthwhile. To be able to compete on such a market the companies focus on a narrow customer segment (market strategy). In this segment the company tries to offer its leading edge in knowledge and technology [Hill, 1993].

New technologies are developed and improved at a fast rate and products that were acceptable to customers yesterday will not do tomorrow. The fast development of new technologies, in turn, decreases the products lifetime i.e. the time for which the product can win customers and add to return of investment. The balance between product development time and product lifetime is therefore of outmost importance. *Smith P. G.* shows the importance of fast releases of new products to market [Smith & Reinertsen, 1991], see Figure 1.

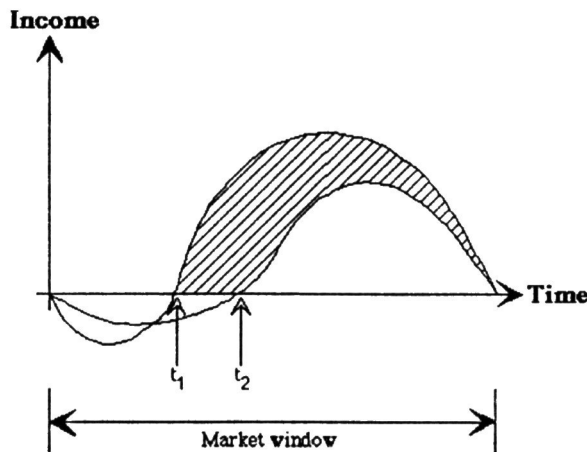


Figure 1. Early introduction of products may increase the product lifetime and market share, [Smith & Reinertsen, 1991]

In the effort to cope with changing customer needs and fast evolving technologies, companies focus on different production strategies. The strategy chosen depends on the type of product, marketplace and customer. An example of this can be seen in a study from the bicycle industry [Ulrich et al., 1998]. Regardless of strategy chosen, however, in the long run the need for a production process that can cope with quick changes in technologies and customer needs is evident. The two main issues are how to be responsive and at the same time handle the impact of change. In order to decrease the impact of change and shorten lead-times companies are trying to implement flexibility in both:

- Product architecture.... and
- Manufacturing² system processes....

Ulrich K shows the interconnection between the two strategies in a matrix see Figure 2 [Ulrich, 1995]. By building the product structure in a modular manner the ability to offer product variety increases though the manufacturing system itself could be rather inflexible and vice versa. The goal for every company large as small, involved in manufacturing of products with high variety would undoubtedly lie at the top right corner of the matrix.

Product architecture	Modular	Variety achieved by combinatorial assembly from relatively few component types Can assemble to order from component inventories Minimum order lead time dictated by final assembly process	May fabricate components to order as well as assemble to order May choose to carry component inventories to minimise order lead time Infinite variety possible when components are fabricated to order
	Integral	High variety not economically feasible; would require high fixed costs (tooling), high set-up costs, large order lead times, and/or high inventory costs	Variety can be achieved without relatively high inventory costs by fabricating components to order Minimum order lead times dictated by both component fabrication time and final assembly time Infinite variety is possible
		Low	High
		Component process flexibility	

Figure 2. Product architecture and component process flexibility dictate the economics of producing variety [Ulrich, 1995].

² This thesis uses manufacturing in the meaning of the physical operations that are required to produce a product [Cochran, 1998]. Manufacturing could therefore be seen as a part of production.

In section 1.2 and 1.3 below the flexibility efforts in product development and manufacturing processes are shortly discussed separately in the following structure.

Product development

Manufacturing

- | | |
|--|--|
| - Reducing lead-time in product development | - Flexible equipment |
| - Increasing flexibility in product architecture | - Control of the Manufacturing system to reduce lead time and increase flexibility |

1.2 Product development (product architecture)

In the product development process two main concerns are lead-time, i.e. time-to-market, and the products ability to support variability.

1.2.1 Reducing lead-time in product development

The product development process could be described as a sequence of steps [Erixon, 1998]. By executing these steps in parallel as much as possible, i.e. “Concurrent Engineering”, the Time-to-market³ can be reduced significantly, see Figure 3.

³ “Time-to-market” is used for the time that elapses between the customer need identification until the product is available for the market.

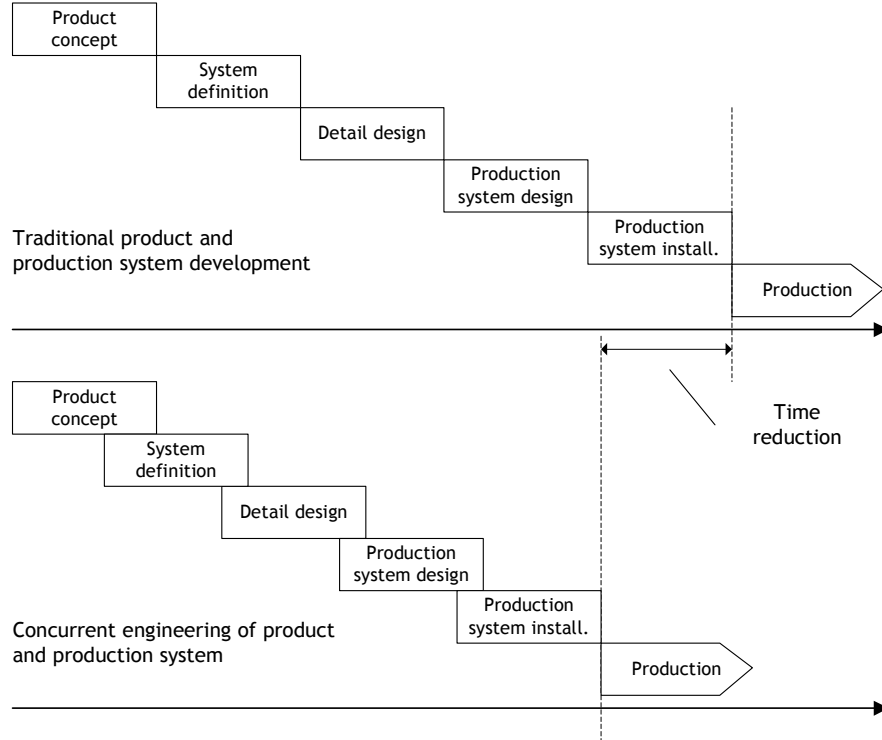


Figure 3. Comparison between the traditional development organisation and Concurrent Engineering (CE) [Erixon, 1998]

By structuring the products in building blocks for instance modules, often called modularisation, it is possible to reduce both the product development time, i.e. Time-to-Market, and increase the flexibility of the product architecture.

Each step in the product development sequence often needs some information from the earlier steps in order to be executed. To reduce the product development time it is essential to handle this information effectively. Modularisation supports this by keeping some of the information constant and provides standardised interfaces so that development of separate modules can be done in parallel. The definition of the term module is not consistent and has a slightly different meaning depending on where in the research community one searches. [Erixon, 1998] defines product modularisation as: "Decomposition of a product into building blocks (modules) with interfaces, driven by company specific reasons."

To reduce product development time, product and manufacturing-processes should be developed in parallel as far as possible as shown in Figure 3. This is a well known fact and mentioned by many authors within different disciplines, see for instance [Bellgran 1998], [Holmstedt, 1998], [Pugh 1991]. A modularised

product supports this by providing interfaces, which work as borders of responsibility. This in turn makes it possible to divide the development of manufacturing processes and their parallel execution.

Sourcing is today a rather commonly used strategy for reducing product development time in larger companies. The reason for sourcing could for instance be due to lack of competence or capacity. For a further discussion on this topic see section 1.5

1.2.2 Increasing the flexibility of the product architecture

To increase the responsiveness for variation in customer orders, i.e. time to customer, flexibility needs to be incorporated into the product architecture. A way to do this is to structure the products in building blocks as mentioned above.

By structuring the products in modules, Time-to-Customer⁴ can often be reduced. One reason for this is that some modules can be common units within a product range and produced to statistical trends at low risk before the order is placed, which reduces the overall lead-time.

Modularised products enable the execution of parallel activities, which, in turn, reduces the lead-time. In this case one could see each module as a product and arrange the fabrication or assembly as a separate module shop, a factory within the factory [Erixon, 1998] see Figure 4.

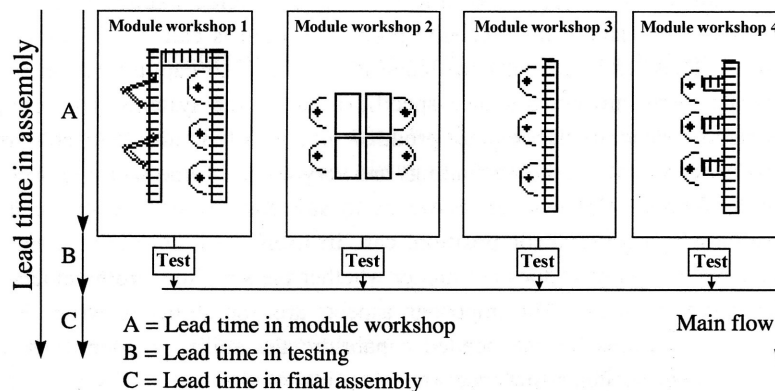


Figure 4. Concurrent assembly of modules [Erixon, 1998]

⁴ "Time-to-customer" is used for the time that elapse between the customer order is placed until it is delivered.

1.3 Manufacturing system policies to reduce lead-time and increase flexibility

The manufacturing system has evolved from the craft-manufacturing at the end of the 19th century via the mass-manufacturing of Henry Ford and Alfred Sloan and the lean-manufacturing introduced by the Japanese car manufacturer Toyota, [Womack et al., 1990] towards what is called agile competition [Goldman et al., 1995].

The mass-manufacturing concept emphasised mass markets, standard designs and high volume manufacturing using interchangeable parts [Hayes & Pisano, 1994]. This is not possible to achieve today except in very narrow niches producing commonality parts.

In the late 1970's, Japanese car-manufacturers introduced the "Toyota Production System" later known as "Lean manufacturing", along with production philosophies JIT, control methods like Kanban, and improvement programs like Kaizen. This took the rest of the world with surprise at the time. Its ability to provide customised products in many variants, at low cost, and despite low volumes, gave the companies significant advantages on the marketplace.

Today, however, the competitive advantages have nearly disappeared due to the fact that most of the competitors are using the lean manufacturing principle as well. In order to be competitive today one must focus more on the company's ability to actually use these principles in a competitive way. One must do things better than the competitors and in a way that is not easily copied. This means that one has to choose a production strategy and attain the organisational skills and manufacturing capabilities according to this strategy. *Hayes* claims that you may for example be able to buy access to certain technology but you cannot buy the ability to produce it effectively, sell it effectively or advance it over time [Hayes & Pisano, 1994].

The objectives for a manufacturing system are to deliver the ordered product at the right time at a minimum cost with an acceptable, i.e. correct level of quality. This means in reality short lead-time, low inventory, low work-in-process(WIP) and effective use of resources. These objectives are magnified by the increasing trends towards short product life cycles and increased product variety. Today in the age of mass-customisation this calls for highly skilled workers and flexible equipment that can easily adapt to new circumstances [Pine et al., 1993].

1.3.1 Flexible Equipment

The use of flexible equipment can reduce the lead-time significantly by allowing fast change-over between variants. Flexible manufacturing technologies have also decreased product lifetime due to its possibilities to fast introduction of new

products or variants. This, in turn, has reduced the risk of competition from “followers”, as the “follower” often competes with a low price product when the product has reached the “mature” phase of the product-life cycle [Meredith, 1987].

Flexible equipment as Flexible Manufacturing Systems (FMS) were installed more commonly during the 1980’s but was introduced already in the late 1960’s. FMS have not spread in the way that was estimated. One of the reasons for this is, according to users, that they have not been giving the return of investment that was expected [Mansfield, 1993].

An FMS system could be defined as “*a production⁵ unit capable of producing a range of discrete products with a minimum of manual intervention. It consists of production equipment workstations (machine tools or other equipment for fabrication, assembly or treatment) linked by a materials-handling system to move parts from one workstation to another, and it operates as an integrated system under full programmable control*” [Mansfield, 1993].

FMS is a technology used predominantly by larger companies. This is due to the fact that they have more resources and are better able to take the risks than their smaller rivals. Another reason is that the system often needs specialised engineering personnel to introduce and operate the system [Mansfield, 1993].

In the case of assembly systems, this effort on flexible equipment has been very interesting since assembly work sets high demands on flexibility and adaptability. Ever since the introduction of the robot there have been efforts to create machines that assimilates the behaviour of human beings. Even if it is not possible to accommodate human flexibility it is important to achieve whatever flexibility possible. There are numerous examples of projects in industry and in the academic world that attempt to achieve Flexible Automated Assembly systems (FAA) with varied degree of success. Some of these projects will be covered in chapter 2. A common belief however is that the FAA technology has not gained ground at the rate it was anticipated [Tichem 99]. Also in the area of FAA it is predominantly larger companies that have implemented the technology. This is one of the problems focused in this thesis as mentioned in the beginning of this chapter.

1.3.2 Control philosophies to reduce lead time and increase flexibility

As mentioned before the marketplace of today needs a responsive system with low WIP and, at the optimum, no inventories. It is obvious that, in order to achieve this, one has to have a control system that supports this at all control

⁵ In this definition production means manufacturing if translated to the previous definition according to [Cochran, 1998].

levels, from within machine systems up to the planning of customer orders. The question on how to control the actual manufacturing system has therefore led to many research projects. Effective manufacturing control systems are those that assure the manufacturing of the right parts, at the right time, at a competitive cost [Spearman et al., 1990].

The manufacturing philosophy Just-in-Time, where nothing should be produced before it is needed and only when it is needed, is an effort to achieve low inventory, low WIP and reduce waste. The two leading philosophies in manufacturing planning and control, on a “customer order” level, are “Push” systems and “Pull” systems. Both are possible solutions to achieve JIT.

Push systems could be defined as the system where manufacturing jobs are scheduled. Pull systems on the other hand could be defined as systems where the start of one job is triggered by the completion of another [Spearman et al., 1990]. Another definition could be “... *a pull system initiates manufacturing as a reaction to present demand, while push initiates manufacturing in anticipation of future demand.*” [Karmarkar, 1989].

Both the push and the pull principle have, of course, its pros and cons and none of them would alone be the best practice; except, however, for the situation suitable for their extremes. Most advanced manufacturing companies need a tailored system including pull-systems like kanban as well as push systems like MRP. [Karmarkar, 1989]. A part of the research in this area has therefore focused on the hybrid systems that can incorporate the advantages of both systems. By using the systems on different time-horizons, the MRP-based push system can plan for future events while the pull system keeps the ongoing manufacturing at a level of satisfactory.

A way to cope with control problems is to reduce the need for control or at least ease the control for the available control systems. What is the control system actually doing?. One could say, very simplified, that a control system keeps track of “what?”, “when?”, “where?” and “how much?”, i.e. what to do, when to do it, what resources to use and to what extent (batch size).

Reducing the amount of parts and the number of different parts would decrease the confusion about “what” to do. To answer the question “when”, the optimal scenario would be to start the manufacturing of a customer order when it is received. To achieve this one must have short lead-times. Short lead-times means small batches, which makes the need for flexible manufacturing systems obvious. A term for this way of controlling the manufacturing is Assembly Initiated Production(AIP) [Arnström, 1997]. The question “where”, is a system layout matter, and could be simplified by modularised products divided into assembly shops as described in Figure 4. Concurrent assembly of modules [Erixon, 1998]. The optimum for the question “how much” would be to do only the ordered amount.

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

By modularising the product one can increase the share of common parts over product variants and by structuring the product in a way that makes it possible to add the customer specific parts or modules late in the manufacturing chain. The control of the system will, hence, be easier.

“Late in the manufacturing chain”, means that the assembly system will play a key role in the manufacturing systems of the future; this will be discussed in the next section.

1.4 The assembly system a key to flexible and responsive manufacturing

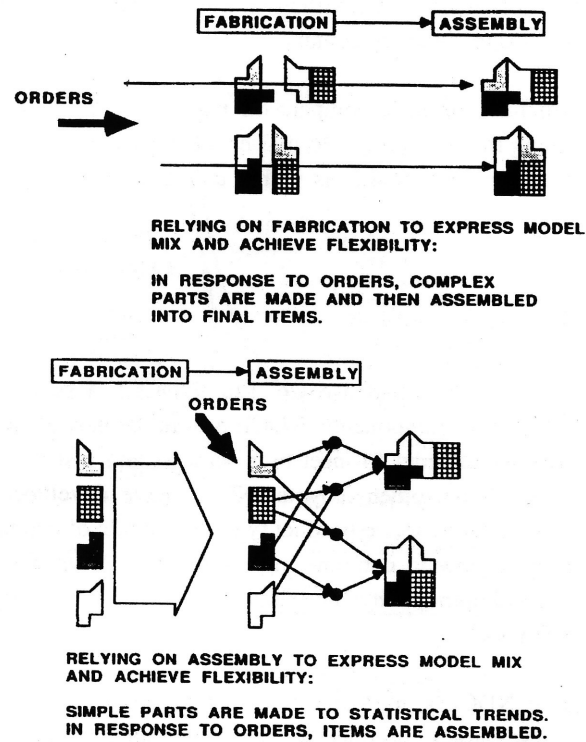


Figure 5. Fabrication driven versus assembly driven variance [Whitney, 1993].

The importance of the assembly system increases in a dynamic environment like today's market. The assembly system have large effects on areas such as:

- Quality
- Flexibility
- Failure Costs
- Time-to-customer
- Strategic issues

The high customer demands increase the need for product customisation leading to an explosion in the number of variants. The variant-creation generates disturbances throughout the whole manufacturing system. A way to reduce disturbances due to variance and increase flexibility is to make the orders customer

specific as late as possible in the manufacturing chain, i.e. in the assembly shop [Whitney, 93] see Figure 5.

The assembly systems effect on quality and flexibility is evident. *Holmstedt*, for instance, points out that the assembly activities in industry are of outmost importance to the companies mainly because it is in the final manufacturing phase that you can control both flexibility and quality [Holmstedt, 1998].

Today's market trends imply that one has to be customer oriented. To be customer oriented means to a large extent that one has to be in control of the assembly process since it is the actual assembly lead-time that will set the limit for Time-to-customer [Arnström & Gröndahl, 1997].

The assembly system becomes a strategic instrument as the company that controls the assembly of the final product tends to own/control the product. Proof for this are the decisions made by large companies to locate the assembly of the final product in the target markets globally to gain quick market specific access to customers and suppliers and the opportunity to develop new operating methods based on local technical development [Feldmann & Rottbauer, 1996].

1.4.1 Assembly automation

The reasons for automating assembly may be several. Some of the reasons include quality, work environment (ergonomics), lack of workforce, miniaturisation etc.

Product quality may be positively affected by assembly automation. Robots are reliable (if correctly applied) and more consistent than human workers. A case study at Sony, studying the assembly of the Sony Walkman showed that the defection rate for manual assembly was 0.1% while robot assembly showed an defection rate of only 0.002% [Makino, 1993]. Quality is also improved more generally when the products are, as a result of the decision to automate, forced to be designed for ease of automatic assembly, i.e. improve of “design” quality [Makino, 1993].

Environmental issues are large motivators for automation. A lot of the work assignments in today’s industrial environment are tasks that should not be carried out by a human workforce. Due to this, every year an important share of the workforce is injured, perhaps for life. This generates a cost for the society that could be avoided if these hazardous operations were to be automated.

Lack of workforce is another reason for assembly automation. The youth’s increasingly critical view of industrial work may lead to a drastic lack of workforce. This is discussed by for instance *Adachi* [Adachi, 1993] and more recently by *Holmstedt* [Holmstedt, 1998]. In Japan this has led to government policies to increase automation.

The miniaturisation of products has created another accelerating need for assembly automation. The products tends to be smaller and smaller and the only way to cope with this is to automate the assembly since the size of the product has made the demands on assembly processes to surpass human capability [Byron et al., 1999]. Some companies as for instance Sony, are using the miniaturisation as a competitive strategy to avoid copies from low wage countries on the market.

Uncoupling of skill and capacity, due to the fast changes in markets, the need for manufacturing capacity varies in time and is hard to predict [Petersson, 1998]. A way to cope with these changes in capacity needs is to have a fixed high skilled workforce as a base and accommodate flexibility by increasing or reducing the output from automated processes. True capacity flexibility however demands flexible general equipment that can be sold to other manufacturers as the capacity demand drops. *Hayes*, for instance, states that if demand picks up again, the company can go out and buy a plant and equipment, but replacing human capital that took years to build will be much more difficult [Hayes & Pisano, 1994].

An effort in the direction of flexible general equipment is the use of Flexible Automated Assembly systems (FAA). The major drawback with FAA systems is

however, that they have not yet proved themselves to be as flexible as manual assembly. FAA-systems will be more thoroughly detailed later in this thesis.

In FAA systems, lead-time reduction can be accomplished due-to fast change-over between, in the assembly system, configured products/variants. Short change-over times makes it possible to reduce batch-sizes and, as consequence, the WIP [Gröndahl, 1987]. In a production view FAA systems can reduce time-to-customer. For instance, some research made in Japanese companies points out that Flexible Assembly Automation, may improve the possibilities for concurrent engineering [Makino, 1993].

The FAA system approach leads, of course, to system flexibility aspects. These will be discussed in section 3.2. A common opinion among researchers within the area of FAA systems is that the use of the systems has not increased the way it was anticipated. The reasons for this are both technical, economical and organisational see for instance, [Tichem et al., 1999], [Langbeck, 1998].

This thesis has its focus within the area of FAA systems and will discuss this area in the following chapters. As described in the introduction to this chapter the thesis also has its focus on small companies and their abilities to increase their technology level in the assembly area. Therefore before continuing the discussion on FAA systems and small companies, the growing importance of the supplier and the small companies importance for the country as such will be detailed.

1.5 The growing importance of suppliers

The role of the supplier has changed significantly during the last part of this century. Long gone is the time when the price to which you could deliver was the sole order-winner. Today the supplier is the tool for companies to e.g. reduce lead-times, gain competence, increase flexibility and maintain quality. Companies tend to reduce the number of suppliers and put more responsibility on the remainders. Suppliers have to take more and more responsibility for development of whole modules or functions in a product, and its future development, an example of this can be seen in the computer industry [Baldwin & Clark, 1997]. Another example of this is the Japanese car manufacturers and their lean manufacturing philosophy [Womack et al., 1990]. A common name for this is “Sourcing”.

1.5.1 Improvement of capabilities by sourcing

The reasons for sourcing could be, for instance, competence, when the actual competence needed is not available in the company. The needed competence could be within product development or advanced manufacturing technologies. This is due to the fact that *“many of today’s products are so complex that no single company has all the necessary knowledge about either the product or the required processes to completely*

design and manufacture⁶ them in-house” [Fine & Whitney, 1996]. Lack of capacity is also a common reason for sourcing. In fact lack of competence and capacity are the two main reasons why a company would seek dependency on suppliers [Fine & Whitney, 1996].

Lead-time reduction can be achieved due to parallel activities in the supply chain. For instance product development time is possible to reduce by allowing parallel development activities at the supplier.

Inventory levels can be reduced significantly by JIT deliveries from the supplier [Womack et al., 1990].

Access to new markets is a large motivator for sourcing. Once a purchaser has established itself in a foreign market as a purchaser, it is then in an ideal position to begin selling goods and services into that market [Bozarth, 1998].

1.5.2 what to make and what to buy

The question concerning what to source and what to not source has triggered vast of research in the management area. A common belief is that one should identify the core business and keep it in the company. A core competence in itself is the ability to make the product specifications and do the right make-buy decisions [Fine & Whitney, 1996].

Three simple principles are presented in literature concerning the decisions on what to source [Venkatesan, 1992]:

- Focus on those components that are critical to the product and that the company is distinctively good at making
- Source components where suppliers have a distinct comparative advantage- greater scale, fundamentally lower cost structure or stronger performance incentives.
- Use sourcing as a mean to generate employee commitment for improving manufacturing performance.

1.5.3 Tiers of suppliers

Suppliers could be sorted in a hierarchy according to how much they contribute to the final product. At the low end would be the suppliers dealing with commodity parts with low margins delivering to the suppliers on the next level, see Figure 6. As one moves up in the hierarchy, the cost-margins improve and the suppliers are gradually taking more responsibility for the outcome of the final product. At

⁶ Manufacture in this case, has the meaning Produce, if translated to the CIRP definition

the top level of the supply chain the supplier has the responsibility to develop and maintain technology edge for a function in the final product.

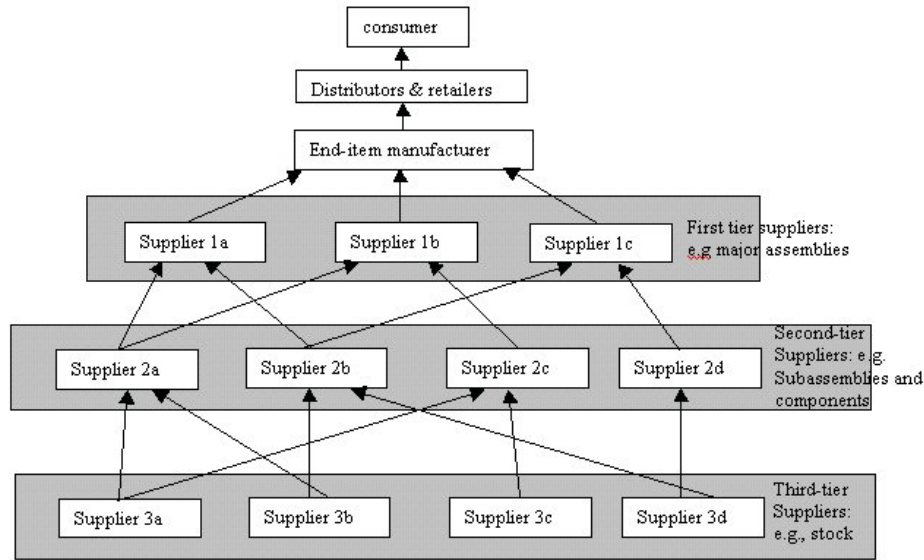


Figure 6. A typical supply chain [Suran, 1998].

The customers, i.e. the supplier on the next level in the hierarchy are, over time, placing higher and higher demands on their suppliers (e.g. supplier 2a is customer to supplier 3a etc. see Figure 6).

In for instance, the automotive industry, the suppliers have evolved from Just-in-Time deliveries via integrated supplies to the most recent modular consortia where the supplier develops a module and assembles it on the company's assembly line [Collins et al., 1997]. This trend of increased responsibility and commitment for suppliers will probably continue throughout other areas in industry as well.

The trend towards tiered supply chains has made competition change from a firm versus firm struggle, towards a competition that is more supply chain versus supply chain [Bhattacharya et al., 1995].

A way to survive, as a supplier in this competition is therefore to qualify as a "good" supplier in a supply chain and learn what the customers on the next level needs. Now, that implies that you need to know the characteristics of a good supplier. Next section discusses this.

1.5.4 Supplier selection practise

To answer the question on what a good supplier is one could look at how different companies choose their suppliers. What criteria do they use? A common belief is that the supplier selection criteria changes depending on where in the supplier hierarchy you are see Figure 7.

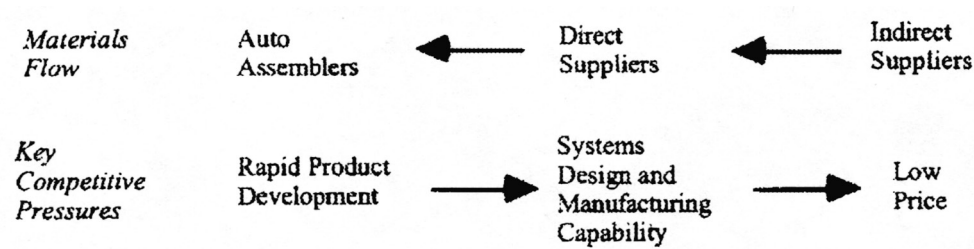


Figure 7. Supplier and key competitive pressures that have to be reconsidered, [Choi & Hartley, 1996].

Lately there have been studies made that proves that this belief has to be reconsidered. A study made on several supply chains in the automobile industry in USA has shown that there is a tendency towards the use of the same criterions at all levels. Surprisingly, the price is one of the least important selection items at all levels in the hierarchy [Choi & Hartley, 1996].

Criteria as ranked in the study, in order of importance:

Criterion	Meaning in the study
1. Consistency	Conformance quality, Consistent delivery and Quality philosophy
2. Reliability	Incremental improvements, Product liability
3. Relationship	Long-term relationship, Relationship closeness, Communication openness, Reputation for integrity
4. Technological capability	Design capability, Technical capability
5. Flexibility	Volume changes, Short set-up time, Short delivery lead-time
6. Price	Low initial price
7. Service	After sales support, Sales rep's competence
8. Finance	Financial conditions, Profitability of supplier, Financial records disclosure, Performance awards

Consistency could be seen as an “order qualifier” criterion while Reliability and Relationship as well as Technological Capabilities and Flexibility are “order winners” (For further discussions concerning the issues “order winners” and “order qualifiers”, see [Hill, 1994]). Reliability and Relationship are mainly management issues. The technical issues such as being a competent designer with high process knowledge and the ability to produce with short lead-times i.e. being flexible comes on fourth and fifth place in the ranking. Its clear that the basis of supplier selection is changing from primarily price based to collaborative/technology/core competency based [Bhattacharya et al., 1995].

The table above could be seen as a hint to suppliers on what capabilities they need to have in order to be a potential supplier within a supply chain. These high demands put on suppliers means both opportunities and the risk to be left outside as the customers rationalise their supply base. At the lower end of the supply base are the suppliers that merely handle commodity parts. The trends towards more long-term supplier relationships and more supplier responsibility means that in-order to stay competitive in the supply chain the supplier must increase his value-adding. The more value added the larger cost margin and larger possibilities to stay competitive. To add value you have to increase your competence, which will in turn differentiate you from your competitors. *Bhattacharya* tries to show the value adding and differentiation of competence and practise at different types of suppliers in a “Value-adding And Differentiation”- matrix, the VAD-matrix [Bhattacharya et al., 1995], see Figure 8.

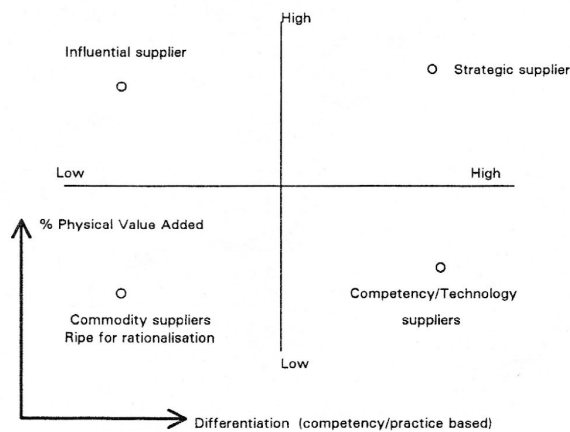


Figure 8. The amount of value-adding and competence decides what kind of supplier you are, i.e. your importance in the supply chain [Bhattacharya et al., 1995].

In the top right corner (Figure 8) the supplier adds both knowledge and value to final product. These kinds of suppliers are strategic and are not likely to be

scrapped by the final assembler. The strategic suppliers are often the suppliers at the top of the supply hierarchy. The competence suppliers have a specific knowledge about a process or technology that makes him important for the supply chain, although they do not add an important share of the final value to the product. At the opposite corner of the VAD-matrix are the influential suppliers that don't add much knowledge but do add a large amount of value to the final product. Finally in the lower left corner are the suppliers delivering commodity parts, parts that add little knowledge and little value to the final products. Figure 9 shows a traditional positioning of suppliers according to [Bhattacharya et al., 1995].

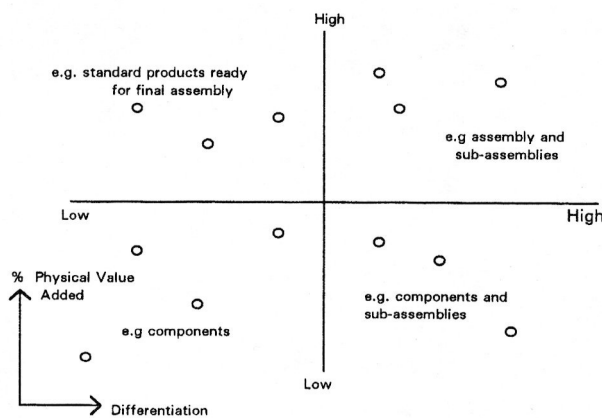


Figure 9. Traditional positioning of suppliers, [Bhattacharya et al., 1995].

As said before dealing with commodity parts involves the risk to be a victim of rationalised supply bases as the long-term relationships develops. In order to be competitive in the future these suppliers have to develop their competence and increase their value adding. Figure 10 shows how the supply base are arranged today.

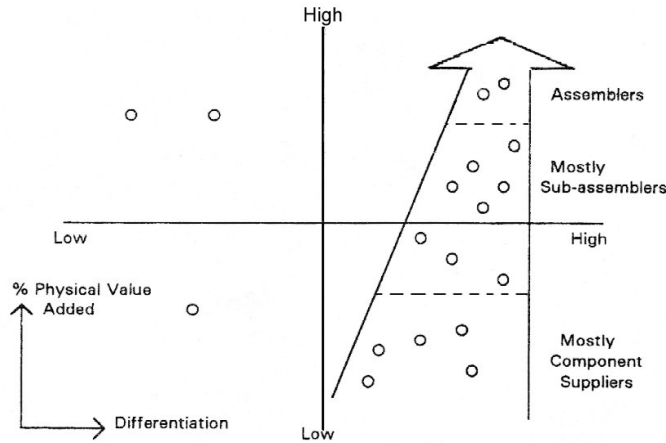


Figure 10. The supply chain of today where suppliers contribute more to the final product [Bhattacharya et al., 1995].

The VAD-matrix implies that in order to be a competitive supplier one first has to move to the right by increasing the competence at the company and thereafter offer more functionality to the final product by moving up in the matrix. The matrix clearly shows that in order to climb up in the supplier hierarchy one have to be an assembler and of course have an efficient assembly system.

The suppliers at the lower end of the supply chain that are forced to do these competitive changes are often small companies. In the study concerning the auto industry discussed above, 74% of the indirect suppliers, i.e. the suppliers not delivering to final assembly, had less than 500 employees [Choi & Hartley, 1996]. Small companies are an important part of a country's infrastructure and the need for them to be competitive in the global market as a supplier is evident. In the next section there will be a discussion concerning the importance of small companies.

1.6 Small companies the potential supplier

Small and medium sized enterprises (companies); SME's, are an important part of a countries economy. Competent SME's, as potential suppliers, attract larger companies to invest in manufacturing facilities within the country. The SME's are not usually a major source of economic trade but they contribute to trade in three other ways. An example from Northern Ireland shows that, [McGloin & Grant, 1998]:

- Small firms acts as suppliers to larger multinational firms in the province.

- New small firms constitute the seedbed from which larger export-oriented indigenous companies grow and emerge.
- The sales and market share which new small firms hold on local markets act as substitutes for potential imports, thus contributing to the strength of the local economy.

SME's often employ an important part of a countries work-force. In for example Northern Ireland the SME's employ almost one third of the workforce [McGloin & Grant, 1998].

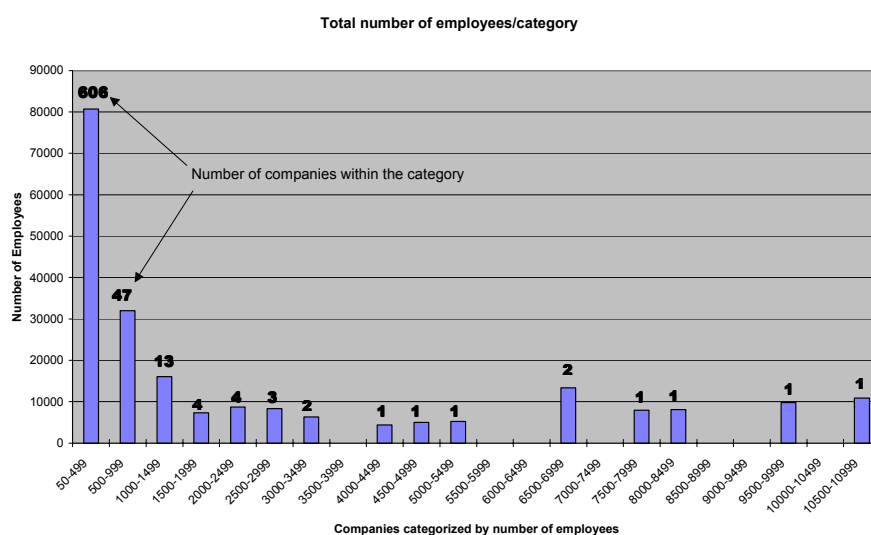


Figure 11. The total number of employees in different company sizes in Sweden⁷.

In Sweden there is similar ratio within industry that deals with manufacturing and assembly of consumer products, here companies with 50- 500 employees stands for approximately 36% of the workforce, see Figure 11. Companies in this category with 50-200 employees stand for approximately 20% of the workforce. In UK, companies with less than 100 workers employ between 40% -70% of the total workforce depending on the source [Mudambi et al., 1996].

In this thesis SME's are defined as companies with < 250 employees.

⁷ The companies in the diagram are selected with the criterion that there should be an industrial application that can involve the assembly of products. Source: UpplysningsCentralen, the UC-select database 1999.

The above reasoning can be seen as an attempt to show the importance of SME's within a country. It is not only that the SME's employ a large part of a country's workforce they are also giving a large contribution by their innovative nature. The SME's are a vital part of the economy for both employment and innovation [Mudambi et al., 1996]. SME's are unique in that way that they often occupy, strategic positions which larger firms cannot economically enter or, areas of high risk large firms dare not go [Brouthers et al., 1998].

Another aspect discussed by *Mudambi* is the degree of flexibility in terms of product quantity and delivery that is unmatched by larger companies. *Mudambi* also claims that the T50 project at the Swedish company ABB was in fact an attempt to imitate the small firms by creating small business units and give these units autonomy [Mudambi et al., 1996].

Due to the above presented positive SME-impact on a country as such, this thesis has one of its focuses on the small company. Another aspect is that since there are so many SME's within a country and since they all need to increase their technology level and value-adding in order to be competitive, according to the previous sections, the market for FAA systems would increase dramatically if the FAA systems could be adjusted to SME needs.

1.7 Research questions of this thesis

In the previous sections the background for this thesis has been outlined. The fast changing marketplace sets high demands on the companies of the future, demands that have forced the development of new ways of designing and manufacturing products. General market trends and trends within design and manufacturing have been discussed. Keys to competitiveness in the market of today are responsiveness (short lead-times) and the ability to handle the impact of change (flexibility).

The assembly system is one important factor in achieving responsiveness and to handle the impact of change. This thesis has therefore one of its focus within this area.

As discussed in a previous section the small company plays an important role in the market mechanism as a supplier of goods and knowledge. However in order to be competitive the small companies need to increase their technology level. Therefore the small company is the second focus in this thesis.

How does one combine these focuses to a research view? In a previous section the use of FAA systems was discussed. The use of these systems has not increased as was anticipated. The fact that small companies need to increase their technology level combined with the fact that the use of FAA systems is not at a

level of satisfactory is the backbone of this thesis. FAA systems have, to date, focused on achieving very flexible and automated systems.

Therefore:

Hypothesis 1: *Developing FAA-systems for SMEs requires a fundamental review of the application of the term “flexibility” as well as more gradual technological and competence implementation phases.*

In order to support this hypothesis there are several research questions that arise:

- RQ1:** What are the functional/operational properties of the FAA systems of today?
- RQ2:** What are the differences between large and small companies concerning the implementation and use of FAA systems?
- RQ3:** How does the implementation process look like in a small company that tries to implement FAA technology? What problems must be solved?
- RQ4:** What are the prerequisites/requirements concerning flexibility and structure posed on FAA systems in order to facilitate the use and implementation of such systems in small companies?

In this thesis the words *implementation* and *installation* have been used according to the following definition: *Implementation* of FAA means to install a system and fully understand the FAA technology and its effects on all areas of the company. In other words, after an implementation one have the “FAA mindset” in the company. To *install* an FAA system means to physically build an FAA system on the shop floor.

The uncertainty that prevails on today’s marketplace causes major problems for most companies. It is hard to predict what production volumes that will be necessary and what product families and variants that will be developed. Furthermore, the life-span of products are decreasing, which in turn makes it hard to justify FAA system investments since the pay-back time will be too short, reflecting the market uncertainty. The reaction in the area of FAA systems has shown itself in attempts to develop very flexible assembly machines hoping that these machines will be able to adapt themselves to different product families and production scenarios. This has led to a series of FAA-system solutions, which will be detailed later (see section 4.1). Another approach has been to focus on the standardisation

and modularisation of high-volume manual assembly lines (see section 4.2.5), also resulting in special robotic cells for the automatic tasks. Flexibility, has been the core issue of most of these developments without a firm grasp of which type of flexibility is being targeted. Because of this, assembly processes has not been focused in an appropriate way. Unfortunately, this existing paradigm of highly flexible (automatic) assembly systems that tries to handle everything (reactive systems) still prevails and results in expensive, highly technological solutions which cannot easily fit into existing production facilities because of the existing products not designed for the system. Furthermore these systems require high technological competence, and are seldom able to assemble more than one product generation.

The thesis will attempt to point out that most of the technology is basically available, although the approach used in its application has flawed. Issues focussed on include how to clarify what is meant by flexibility, how to truly enhance and facilitate the implementation of such technology, and what remains to be done in terms of the missing technology. Since SMEs denote low competence levels and limited financial resources, they may represent the ultimate challenge to systems that term themselves flexible. Basically, any flexible system that is truly applicable in SME environments would definitely represent a low risk (technological and financial) application.

1.8 Delimitations

This thesis deals with final assembly of products or subassembly of products. The size of the products must be in a range that is suitable for robotic assembly systems. This thesis do not take into account the specific problems concerning the assembly of products that are very small and falls into the category of micro-assembly or mini-assembly [Byron et al., 1999].

This thesis deals with the structure and flexibility of Flexible Automatic Assembly (FAA) systems in order to support the implementation in small companies. The results from this thesis will give proposals on actions to take in FAA system development and implementation strategy in order to facilitate the implementation process of FAA systems in small companies. The main focus is on hardware solutions and the way they can be arranged and developed. Although the control system is of outmost importance in an automated system that claims to be flexible, this is not the main focus of this thesis.

1.9 How to read this thesis

In order to consolidate the hypothesis, and obtain answers to the given research questions, the work detailed in this thesis has been structured as follows:

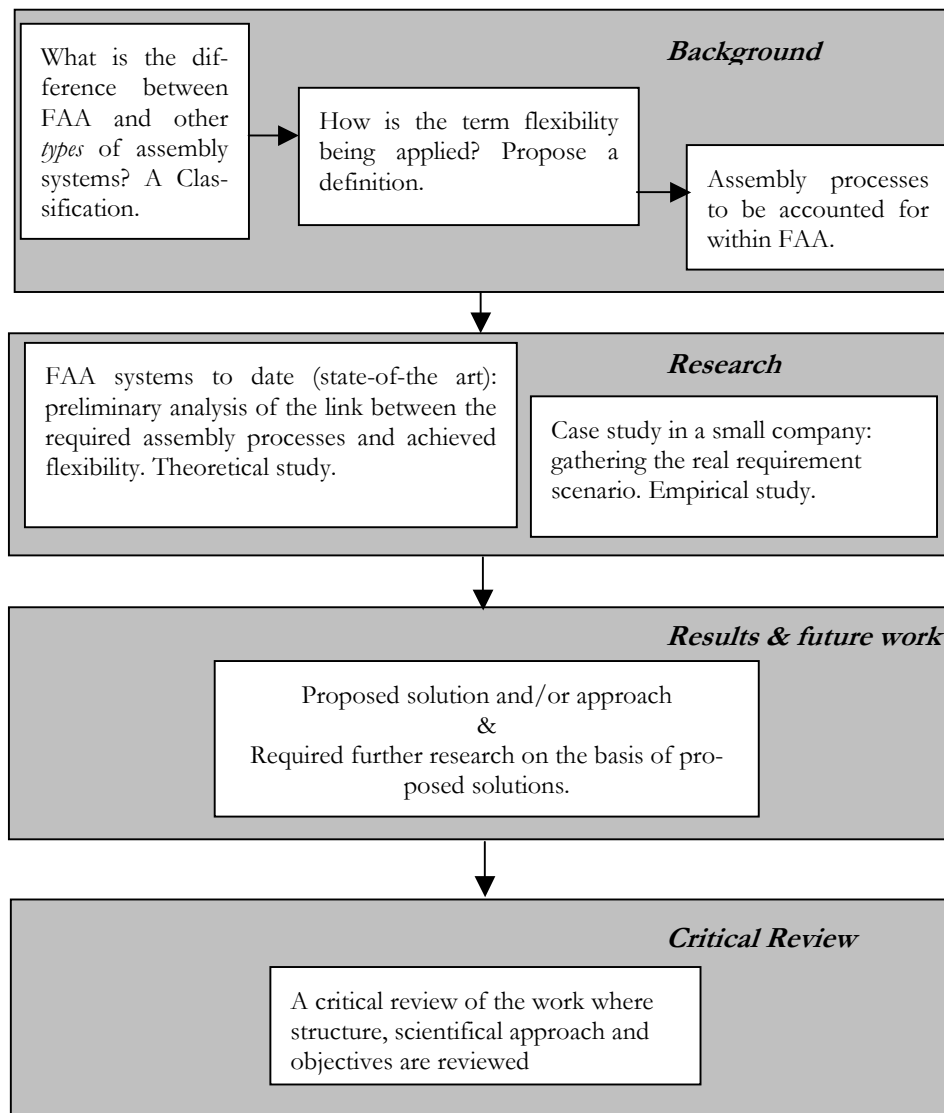


Figure 12. A map showing the structure of this thesis.

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

To further guide the reader through this thesis the table below is a guide on the content, and what are trying to be achieved in each chapter.

Table 1. A guide on the content of this thesis.

Chapter 1	Chapter 2	Chapter 3 & 4	Chapter 5
What is the problem? Introduction to the market of today and what it means for the small company. Based on the problems described research questions are presented.	Scientifical Approach A presentation of the scientifical approach of this thesis.	What has been done? Two chapters where related work is presented. FAA-systems are defined and assembly processes are discussed. FAA-systems are analysed.	Small company situation? A case study in a small company where efforts to install an FAA-system is studied. Implementation and installation issues are discussed.
Chapter 6	Chapter 7		
Requirements? Discussion on system requirements in order to implement FAA into small companies based on literature studies and the case study. Proposed approach a FAA-system approach is proposed to facilitate implementation of FAA into small companies. Furthermore, a way to prioritise flexibility efforts is introduced and proposed future research is also presented.	What has been achieved ? A critical review of the work done such as: - Research structure - Scientifical approach - Objectives of this thesis.		

2 SCIENTIFIC APPROACH

In this chapter the scientific approach adopted in this thesis is described. First engineering as a science is shortly discussed. The scientific view is then outlined for this thesis. Case study as a scientific method is presented. Finally the research questions and the method used to answer these questions are described.

The research presented in this thesis, the conclusions drawn and presented proposals to solutions are all reflected by the view of reality that the author has developed during the research. This view of reality has primarily been supplied to the author by representatives from the research community, within which he serves, in writing or through seminars and discussions. Since the author's work is only a tiny part of the total knowledge within the community, it is without saying that the work has to be built upon previous research and thereby knowledge. In order to be able to build upon previous work there has to be a common view of reality. Observations, data collection and conclusions are all determined by the chosen view of reality [Arbnor & Bjerke, 1994]. After all, what is the value of a probability calculation for the risk of falling over the edge of the earth, to an advocate of the belief that the earth is a sphere [Arbnor & Bjerke, 1994].

2.1 Engineering and science

Engineering as a science has not been accepted until most recently and still there is advocates of the belief that engineering is merely a matter of craftsmanship and not true science. Science was developed as an activity with no other goal than to increase knowledge [Sohlenius, 1990]. However in order to develop society there is a need for designing tools and methods outgoing from the knowledge gained. This is where engineering plays a vital role. The difference between the engineer and the scientist is [Sohlenius 1990]:

- The scientist explores what is
- The engineer creates what has never been

Outgoing from the above two statements the paradigm of **the Science of Engineering** is proposed to be understood from the following [Sohlenius, 1990].

The engineering scientist...

1. **Analyses** what is
2. **Imagine** how it should be

3. **Creates** what has never been
4. **Analyses** the results of the creation to the benefit of mankind.

Another distinction often made between **science** and **engineering science** (or Science of Engineering) is that **science** is concerned with observations and explanations of the natural world, and therefore also called **natural science**, while **engineering science** is concerned with observations and explanations of phenomenon created by mankind. Figure 13, shows the interrelationship between Natural science and Engineering design (another word for engineering science) as perceived by [Braha & Maimon 1997].

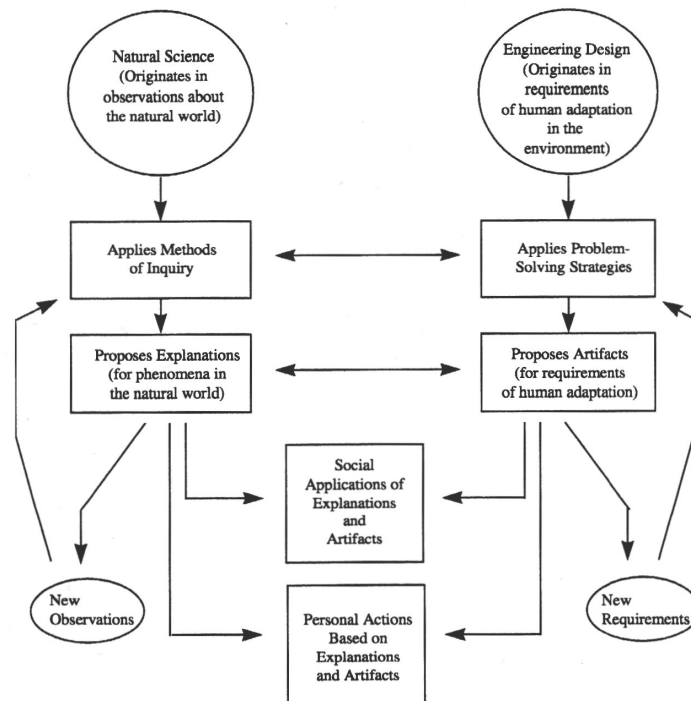


Figure 13. The interrelation between Engineering design (or engineering science) and Natural science [Braha & Maimon, 1997].

2.2 Different views of reality

The use of research method depends highly on the view of reality, i.e. how the reality fit together. There exist three dominant views [Arbnor & Bjerke, 1994]:

- The Analytic view
- The System view

- The Actor view

The analytic view is the oldest and is built upon the assumption that the whole is completely represented by the sum of the parts. By studying and understanding the parts it is possible to summon up and understand the whole.

The system view assumes that the reality is arranged in a way that the whole is not the same as the sum of the parts. This implies that the interaction between parts is important for the final result. In the system view knowledge and results are system dependent. In a system view the parts are understood outgoing from the properties of the whole.

The actor view assumes that the reality, the whole, is understood outgoing from the properties of the parts. The reality is considered to be a social construction and knowledge generated is dependent on the individual.

The research in this thesis builds upon a system view. Good solutions to FAA processes do not summon up to good FAA systems. Instead, FAA systems must take into account more demands than specific process demands, i.e. good interactions between processes may compensate for individually not optimised processes.

2.3 Research strategy

As a practitioner of science of engineering and with a system view of reality the author still have to have a research strategy that would fit the problem and the questions that are to be answered.

As a research strategy, the case study is used in many situations. *“In general, case studies are the preferred strategy when “how” or “why” questions are being posed, when the investigator has little control over events and when the focus is on contemporary phenomenon within some real-life context”* [Yin, 1994]. There exist five major research strategies and which one to use depends on three conditions [Yin, 1994]:

- Type of research question posed
- The extent of control the investigator has over actual behaviour events
- The degree of focus on contemporary events as opposed to historical events.

Table 2 below shows different research strategies depending on the status of the three conditions above [Yin, 1994].

Table 2. Relevant situations for different research strategies. [Yin,1994].

Strategy	Form of research question	Requires control over behavioural events	Focuses on contemporary events?
Experiment	How, why	Yes	Yes
Survey	Who, what, where, how many, how much	No	Yes
Archival analysis	Who, what, where, how many, how much	No	Yes/no
History	How, why	No	No
Case study	How, why	No	Yes

When studying small companies, and their efforts on implementation of FAA it should not require control over behavioural events and the focus is most certainly contemporary. Some of the research questions are “how” questions so it seems that the use of a case study approach would be appropriate for some of the research questions. As a complement and for answering the “what” questions a literature survey is performed. Table 3, shows research question and applied research strategy.

Table 3. Research question versus research strategy.

	Question	Method	Science engineering
RQ1:	What are the properties of the FAA systems of today?	Litt. study	Analyse what is
RQ2:	What are the differences between large and small companies concerning the implementation and use of FAA systems?	Litt. study + Case study	
RQ3:	How does the implementation process look like in a small company that tries to implement FAA technology? What problems must be solved?	Case study	
RQ4:	What are the prerequisites/requirements concerning flexibility and structure posed on FAA systems in order to facilitate the use and implementation of such systems in small companies?	Litt. study + Case study	Imagine how it should be + Create what has never been

According to what was discussed earlier concerning science and engineering, research question 1 – 3, in Table 3, focus on “*Analyse, what is?*”. Research question 4 focuses on “*Imagine how it should be*” and “*Create what has never been*”. Described in another way one can say that chapter 1 to chapter 5 in this thesis focuses on “*Analyse what is*”. Chapter 6 addresses “*Imagine how it should be*” and “*Create what has never been*”. Chapter 7 deals with “*Analyse the results for the benefit of mankind*” see Table 4.

Table 4. Science of engineering steps and corresponding chapters in the thesis.

Science of engineering steps	Chapter
- Analyse what is	1, 3, 4 & 5
- Imagine how it should be	6
- Create what has never been	6
- Analyse the results for the benefit of mankind	7

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

3 FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

This chapter intends to describe the FAA system as such and the key processes and flexibility issues involved. Flexibility concepts and terminology used in this thesis will be explained.

This chapter will cover three main issues. First of all a clear picture of what FAA systems are will be given in order to differentiate them from other assembly solutions. Hence the placing of FAA systems within a given scenario.

Secondly, flexibility and its use within the application of FAA systems will be discussed and analysed. This is of particular relevance since flexibility implies many issues, such as competence level requirements, economical adaptability, technological aspects, and so forth. The users of FAA deserve to be given a far more able understanding of the underlying implications of such a term as FAA. This section will propose a more practically viable definition.

Thirdly, a short description of the processes to be accounted for in an assembly are described. This is done in order to analyse, at a later stage (see chapter 4), how the FAA solutions to date have been applied in terms of the actual assembly processes and their promised flexibility. Another objective with this description is to attempt to achieve a common language (discussion platform) between the author and reader.

Ever since the Industrial Robot^{8 9} (IRb) saw its light, there have been continuous efforts to assimilate the human abilities in the sense of adaptability and flexibility. This is especially important in the area of assembly. The Industrial robot has particularly contributed to the development of flexible automated assembly systems with the ability to cope with different product-variants and even different products.

⁸ According to Robotic Industries Association(RIA) the definition for an Industrial Robot is:

“ A robot is a reprogrammable multifunctional manipulator, designed to move materials, parts, tools or specialised devices through variable programmed motions for the performance of a variety of tasks.”

⁹ Definition according to International Standard ISO 8373:1994(E/F) : Manipulating industrial robot - Automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes, which may be either fixed to place or mobile, of use in industrial automation applications. The robot includes - the manipulator - the control system (hardware and software)

3.1 Classification of the FAA system

Assembly systems can be categorised according to how well they can adapt to changing circumstances or according to how they realise the value-adding [Björkman, 1990]. A system that, can adapt to change is considered flexible, otherwise it is considered dedicated. The system can be realised through automation of equipment or by a manual workforce. Table 5 shows in a matrix the different categories of an assembly system. The table is a summary of *Björkman's* categorisation of assembly systems[Björkman, 1990].

Table 5. Classification of assembly systems according to [Björkman,1990].

	Flexible	Dedicated
Manual	Manual assembly systems that can easily change assembly processes and workflows to new products or product variants.	Manual assembly systems that are “locked” into a specific workflow by organisational reasons. Or Manual assembly systems that cannot be easily changed due to the use of specific high cost fixtures and tooling.
Automated	Flexible automation, in which flexible equipment such as industrial robots, are used.	Hard automation where equipment is very product specific and very hard to use for other products. The majority of the assembly operations are automated.

There is no sharp border between the different types of assembly systems described above. For instance, at what degree of automation is a manual assembly system to be considered an automated assembly system? In recent years “hybrid” systems have been developed that tries to take advantage of both the flexibility of the manual workforce and the efficiency of the automated equipment, see for instance [Arnström et al., 93]. There is however no use in knowing whether it is a manual or automatic system. It is more interesting to know what ability different systems have. *Lotter* classifies different assembly systems according to their ability or

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

suitability to manage a certain product complexity at a certain production rate [Lotter, 86], see Figure 14.

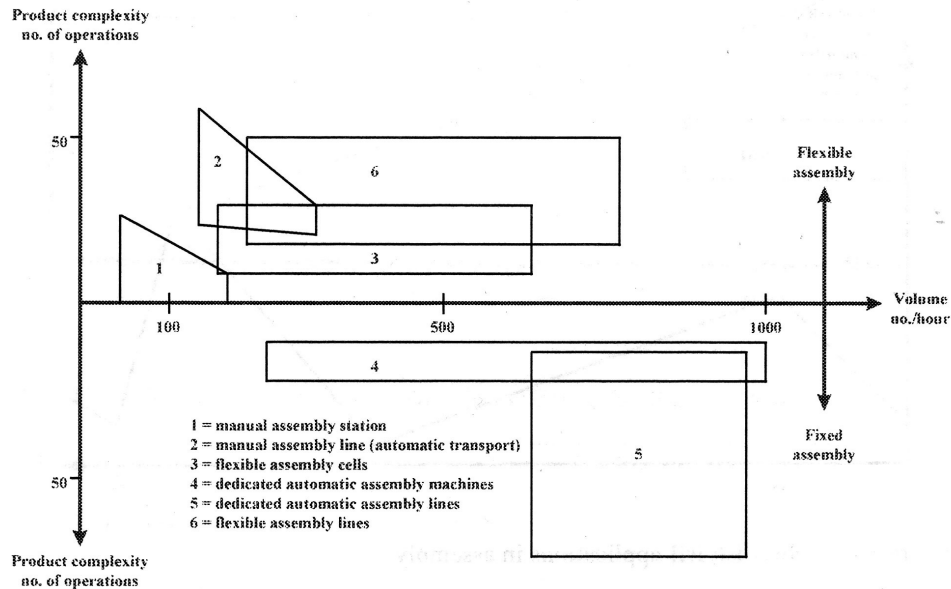


Figure 14. Classification of different assembly systems [Lotter, 86]

According to the classification in Figure 14, manual assembly stations can handle less product complexity than manual assembly lines, flexible assembly lines or even (in some cases) flexible assembly cells. This is however due to the rather simple definition on product complexity. The number of operations as a measure of product complexity does not take into account the various assembly problems in an assembly process such as feeding and mounting. The classification is merely outgoing from speed, i.e. how many products can be assembled within an hour if the assembly consist of a certain number of operations. If the scale in Figure 14 is linear, a flexible assembly cell (area 3 in the figure) according to Lotter is an assembly cell suitable for products with approximately 10- 35 operations and a production rate ranging from approximately 150- 600 assemblies per hour (270 000 – 1080 000/year, 1shift, 1800 h/year).

Another classification outgoing from the systems suitability, concerning yearly volumes and number of variants for the various assembly systems is made by [Langbeck, 1998] see Figure 15. The curve that the figure is based on comes from a survey made in French industry studying the yearly volume for products [Geslot, 1989].

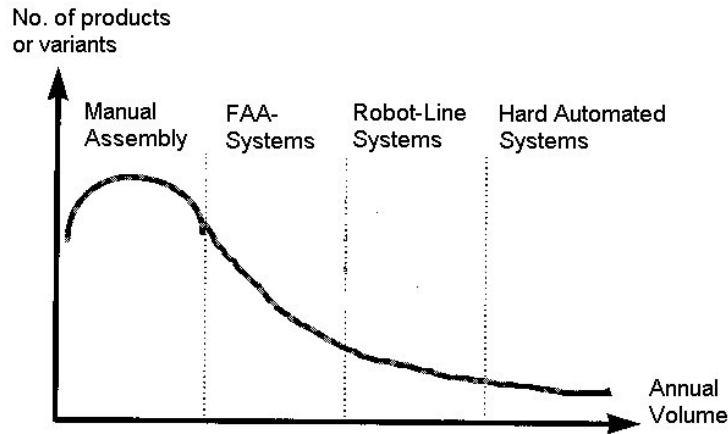


Figure 15. Classification of assembly systems according to their suitability at present concerning annual volume and number of variants [Langbeck, 1998]. The curve comes from a survey made by [Geslot, 1989].

Flexible Automatic Assembly (FAA) systems are systems that incorporate a large portion of flexibility and still can manage a rather high yearly volume. These systems use flexible equipment that facilitates fast changeover between planned product variants. The research within FAA strives for moving the border between FAA systems and manual assembly systems further to the left in Figure 15 since the largest part of today's products are within the area of manual assembly.

Note that it is not uncommon to find that FAA systems may relate to two very different production flow categories. Some FAA systems refer to line type solutions whereas other to cell-type. A classification of the differences is therefore necessary. Line configuration and cell configuration are two separate approaches within the area of FAA systems. The approach depends mainly on the yearly volume but also on product complexity, variants etc. The term assembly cell is often used in two concurrent meanings. The term assembly cell is used for a one-station assembly system and in the meaning of a station or standardised component within a assembly line. *In this thesis the term FAA cell is used in the meaning of a one-station assembly system and the term FAA station in the meaning of an FAA cell within an FAA line.* The difference between an FAA line and an FAA cell could be described as in Figure 16 below [Makino, 1989].

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

	FAA line	FAA cell
Process	Divided	Integrated
Transfer	Done	Not for a single-robot cell
Task of each station	Simplified	Complex
	Specialised	Versatile
	Standardised	Not Standardised
Cycle time	Short (3 - 60s)	Long (20s - 3 min)
Flow of workpieces	In-line	Circulating
	one way	Network
No. of robots	2-100	1-4
No. of assembled parts per robot (IRb)	1-6	1-50
Tool change	Single tool	Turret tool
	Multi finger	Switchable tool
	Turret tool	ATC (Automatic Tool Change)
Production vol.	High	Low

Figure 16. The difference between line-structured and cell-structured FAA systems [Makino, 1989].

In FAA lines the assembly process is divided between several FAA stations. Due to high volumes, the cycle time for each station has to be decreased. As cycle-times decrease the need for more simplified, specialised and standardised operations increases. In a line-configuration, operations are performed in parallel and, after the warm-up sequence of the system; the lead-time will be equal to the cycle-time of the slowest station. Since the line-configuration demands the workpiece to be transferred between stations, the transfer process is very essential. The stations in an FAA line perform a few operations but the parts may be used in several stations so the transportation process and feeding process can be rather complex. Few operations mean few tools or multi-purpose tools.

In the case of FAA cells the assembly process is integrated and the whole assembly is performed within the cell. FAA cells are used for low to medium volume products where the goal is to assemble many different products or variants to reach a total volume that can justify the investment cost. The transfer process is quite lim-

ited in the single IRb cell. There are often not more than four IRbs in a cell, which means that each IRb has a longer cycle-time compared to the FAA lines. Each IRb has to handle more tasks, which means complexity and need for versatility. Along with the complexity and versatility the amount of tools increases and the need for fast tool changes is evident.

“Another difference between cells and lines could be that cells are groups of self-contained workstations. Each cell has power connections, air couplings and a computerised control system. A cell can operate independently or with other cells.” [Ericsson, 1996].

3.2 Flexibility in FAA systems

In reality, there is no distinct border between a dedicated and a flexible system. For instance, if a system is designed for assembling 20 variants at present, is it then so that this system is flexible, or is it to be considered dedicated to these 20 variants? What is it that makes one system more flexible than another?

There are many authors that have tried to define flexibility. A survey made by *Petersson* showed that there exist more than 26 definitions of flexibility in literature [Petersson, 1998].

Björkman divides the flexibility into two perspectives, the company as a whole (economic flexibility) and the assembly system as such (technical flexibility) [Björkman, 1990]. A system that is highly flexible from an assembly system perspective is not necessarily flexible in a company perspective. A dedicated assembly system with a low technical flexibility and short payback time can sometimes be more flexible from a company perspective (economic flexibility), if the near future is uncertain [Björkman, 1990]. There is, however, a risk in using payback time as a measure for economical flexibility. There is risk of losing market shares due to too long rebuild time when an old dedicated system is paid for and a new system is to be built from scratch [Björkman, 1990]. *Björkman* concludes that in order to consider the flexibility in terms of profitability both economical- and technical flexibility have to be considered. *Björkman* further uses three definitions of flexibility¹⁰ [Björkman, 1990]:

Re-use flexibility:

The ability to economically re-use an assembly system that is no longer useable in its present state. Equipment with a high rest value in relation to the investment cost is considered to have high re-use flexibility. That is, if the systems structure is designed in a way that makes re-use of equipment economically possible.

¹⁰ These three definitions are translated from Swedish with the risk of adding yet another term. The Swedish terms for the definitions are “Återanvändningsflexibilitet”, “Användningsflexibilitet” and “Anpassningsflexibilitet”.

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

Operation flexibility: The system or equipment's technical usability and adaptability. This flexibility refers to the equipment's ability to change the state of a single object in many ways or change the state of many different types of objects. This flexibility also refers to the systems ability to change between different products that the system has been designed for and the ability to change to totally new products.

Adaptation flexibility: The systems ability to adapt to new products at a reasonable cost. High cost for adaptation means low adaptation flexibility.

Björkman further adds the term change-over flexibility as a common name for Operation- and Adaptation flexibility. [Björkman, 1990].

Chryssolouris tries to define a measurement for flexibility by defining flexibility as the sensitivity for change; i.e. the lower the sensitivity the higher the flexibility [Chryssolouris, 1996]. He defines the measure as penalty of change: $POC = \text{Penalty} \times \text{Probability}$. This is an interesting flexibility measure because it pinpoints the core problem. If there were to be no penalty for change there would be no use in working with flexibility issues. A problem here, however, is to verify what the true penalty is for various changes and quantifying it. The probability term in the flexibility definition is also important. Since it would be too ambitious and costly to be flexible to everything one has to focus on the important issues. By combining the probability for an event to occur, that demands change, with its penalty one can more easily focus on the right type of flexibility. An interesting conclusion from this measure is that a system that can accommodate changes that would never occur is not very useful and should not be considered flexible. In other words, a system should not be considered inflexible when it has a high penalty for changes that have little probability of occurring [Chryssolouris, 1996]. This implies that the same system can be seen as flexible within one company and be considered inflexible in another since there are different probabilities for changes. The question on how flexible a system one should have now in order to accommodate changes in the future [Chryssolouris, 1996], is however highly relevant within FAA.

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

Chryssolouris defines three main categories of flexibility within manufacturing systems as such [Chryssolouris, 1996]:

Product flexibility: Enables a manufacturing system to make a variety of part types with the same equipment. Economically using small batch-sizes to quickly respond to demands for different products. Equipment can be used across multiple product-life cycles increasing investment efficiency.

Operation flexibility: Ability to produce a set of products using different machines, material, operations and sequence of operations. Operation flexibility results from the flexibility of processes, machines, product designs and the flexibility of the manufacturing system structure.

Capacity flexibility: Allows a system to respond to demands by varying output volumes while remaining profitable. It reflects the ability of the manufacturing system to contract or expand easily.

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

W.E Bodine, Vice President of The Bodine Corporation talks about three levels of flexibility within an assembly system [Bodine, 1993]:

- | | |
|-------------------------------------|--|
| Level 1, Change-over flexibility: | The ability for an assembly system to handle variations among a family of products. Only a minimal of change-over is required as the product variations are known and are planned for when designing the system. |
| Level 2, Product flexibility: | The ability to accommodate future product changes. This may require adding or revisiting of tooling and product design. Even though the actual product changes are unforeseen, it is often possible to identify the affected areas and types of changes. |
| Level 3, System re-use flexibility: | The ability to produce a completely new product by (cost-effectively) re-tooling or re-engineering of the assembly system. This is in many respects the most challenging form of flexibility, the degree of modularity of the system being the key to its potential for being re-used. |

These three levels can be seen as three different time-horizons where level 1 represents the daily issues and level 2 has a longer time-perspective, dealing with introduction of new product variants. Level 3 deals with the introduction of new products and the time-horizon depends on the product-life-cycle. Basically, it seems like *Björkman* and *Bodine* above are describing the same types of flexibility, but are using different terms for it.

Landqvist and Papinski defines several types of flexibility within FAA [Landqvist & Papinski, 1983]:

- | | |
|-----------------------------|---|
| <u>Product flexibility:</u> | The ability for a system to accommodate changes necessary for new products. |
|-----------------------------|---|

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

Variant flexibility: The ability for a system to accommodate changes necessary for assembling a new variant of an existing product

Batch flexibility: The ability for a system to change between different products or variants previously assembled in the system.

Geometrical- /Technical flexibility: The equipment's ability to perform various operations on objects with different geometrical shapes.

Routing Flexibility The ability for a system to change the sequence of assembly operations.

Also in the above definitions one can see different time horizons from new products to changes between batches in the system.

Johansson defines two types of flexibility in FAA systems referring to two different time horizons or scopes [Johansson C., 1981]:

Interior flexibility: Refers to the systems ability to, during the assembly process, handle and mount parts of various geometrical shapes. It is a measure for an equipment's real-time flexibility/adaptability.

Exterior flexibility: This flexibility is defined as the assembly systems ability to be changed, manually or automatically, in order to assemble product variants.

Interior flexibility can be seen as the ability to act upon changes that occur inside the system at runtime, while exterior flexibility is the ability to respond to demands posed on the system from the outside.

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

A further exploration within the jungle of flexibility terminology reveals a rather extended definition for manufacturing systems in general, made by [Browne et al., 1984]:

Production flexibility: The universe of part types that the manufacturing system can produce.

Process flexibility: The ability to produce a given set of part types, possibly using different materials, in different ways.

Machine flexibility: The ease of making changes required to produce a given set of part types.

Product flexibility: The ability to change over to produce new (set of) products very economically and quickly.

Volume flexibility: The ability to operate profitably at different production volumes.

Operation flexibility: The ability to interchange ordering of several operations for each part type.

Routing flexibility: The ability to handle breakdowns and to continue producing a given set of part types.

Expansion flexibility: The ability to expand the system easily and in a modular fashion.

Andreasen & Ahm discuss flexibility in assembly systems and look at flexibility from a life-cycle perspective of an assembly system [Andreasen & Ahm, 1986]. To avoid further introductions of terminology the Danish terminology have not been translated into English, the terms within parenthesis are just labels used in Figure 43 on page 129. Instead the various phases in the system life cycles are focused and the explanation for each flexibility type is outlined:

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

During the design phase of the system: (Design flexibility)	The assembly system's ability to be structured according to the potential product range during the design phase. A high level of flexibility at this stage decreases the investment risk and shortens the installation time of the assembly system (for a comment on this see page 49).
During the ramp-up phase: (Ramp-up flexibility)	The assembly systems ability to be quickly adapted into production-mode. This means that the system will quickly reach the capability that was planned for during design.
At run-time: (Run-time flexibility)	The assembly systems insensitivity to variation in the assembly processes. A low sensitivity to variation means high availability.
Introducing new planned product variants: (Planned changes flexibility)	The assembly systems ability to be easily adapted to new product variants that have been planned for during design of the system. A high degree of this flexibility means short change-over times. Low investments risk.
Introducing new products into the system.: (Unplanned changes flexibility)	This flexibility refers to the assembly systems ability to be adapted to variants that have not been planned for. This could be unforeseen product changes or products or variants that had low priority in the design phase of the system.
When rebuilding the system for new products: (Rebuild flexibility)	The ability to totally rebuild the system to other products.

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

Gerwin has similar definitions on flexibility as the above-mentioned authors. The definitions are focused on manufacturing systems in general and are not specific for assembly systems [Gerwin, 1983]. The six flexibility definitions are the following:

<u>Mix flexibility:</u>	The ability to, at an arbitrary point in time handle a mix of different parts with similarities.
<u>Part flexibility:</u>	The ability to add or remove parts from a mix over time.
<u>Design flexibility:</u>	The ability to rapidly accommodate changes in a part's design.
<u>Routing flexibility:</u>	The ability to re-route a part within a system in case a production unit would fail.
<u>Volume flexibility:</u>	The ability to accommodate the volume fluctuations for a given part.
<u>Material flexibility:</u>	The ability to handle unforeseen variations in dimensions or quality.

Flexible Assembly Systems are configured mainly for two types of flexibility, *Static flexibility* and *Dynamic flexibility* [Allingham, 1990]. Static flexibility is referred to as the possibility to rebuild the system for other products, i.e. off-line adaptability. Dynamic flexibility is referred to as the systems ability to adapt to changing circumstances during run-time i.e. on-line adaptability. These two flexibilities tend to have a negative correlation. “*Ironically, static flexibility of a given system may decrease as dynamic flexibility is added, depending on the specific hardware used*”, [Allingham, 1990]. A way to decrease this tendency is to use a modular system approach [Allingham, 1990].

3.2.1 Flexibility summary

In the above section a large amount of flexibility concepts and terminology was presented. Most of the concepts are describing how well a system can manage to change to new circumstances. Not many of the concepts tries to define how well a certain system manage change, i.e. a quantitative measure. Instead, most of the concepts describe IF a certain system can handle a certain change, that is, if the system can react upon an event in its environment and adjust to it. Some of the flexibility concepts focus on handling change during different life-phases of a system while some of them focus on flexibility during certain process stages etc. A good purpose with the flexibility concepts described is that they form a terminology that can be used when discussing flexibility. The next section describes the terminology used in this thesis. An attempt is made in this thesis to structure these flexibility concepts and create a quantitative measure by looking on the frequency and horizon of events that force a system to handle change, see section 6.3, page 126.

3.2.2 Flexibility terminology used in this thesis

In this thesis, a clear distinction is made between flexibility at system run-time and flexibility referring to adaptability (through rebuilding or reconfiguration), while the system is off-line. For this distinction, the flexibility terms *dynamic flexibility* and *static flexibility* are used see Figure 17. *Dynamic flexibility* can be seen as the ability to, at run-time, act upon scenarios that the system is configured for i.e. the scenarios are anticipated and planned for. *Static flexibility* is the ability to change the system by off-line reconfigurations or total rebuild. A system is in this thesis stated to be reconfigured if only product specific equipment is changed e.g. tooling, feeders and fixtures. A system is considered rebuilt if the whole system is changed including the system layout.

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

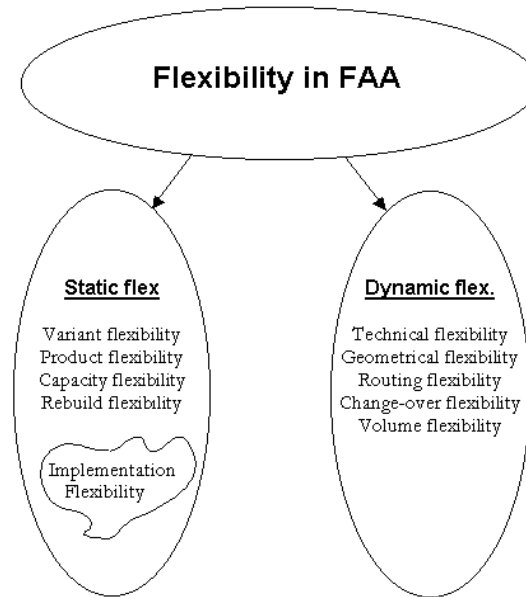


Figure 17. Flexibility in FAA systems as used in this thesis.

Dynamic flexibility

Dynamic flexibility can be divided into some sub-levels referring to various flexibilities concerned with the adaptability during run-time. *Technical flexibility* is in this thesis used for the systems ability to handle different operations on an object. *Geometrical flexibility* is used for the systems ability to handle part types with different geometrical shapes. *Routing flexibility* refers to a systems ability to handle changes by changing the sequence of operations, batches or orders. *Change-over flexibility* is used for a systems ability to change between different products or variants for which the system has been configured. *Volume flexibility* is referred to the systems ability to vary the output volume within its capacity limits.

Static flexibility

Static flexibility can also be divided into sub-levels where the term *Variant flexibility* is used for the systems ability to be configured for a new product variant planned for. *Product flexibility* is used for the ability to configure an existing system for a new product or variant not planned for. The term *Capacity flexibility* is here used for a systems ability to easily expand or contract its capacity limits. *Rebuild flexibility* is used for the systems' ability to be totally rebuilt for new circumstances.

A flexibility that is missing here is the ability for a system principle to support an easy implementation. This thesis focuses on implementation of FAA systems into small companies and believes that there have to be systems that support the process of implementing FAA. This thesis therefore adds the term *Implementation flexibility*. This flexibility is considered a static flexibility. This thesis will further develop the meaning of this term.

3.3 Key areas in FAA systems

Any assembly system consists of four key processes [Makino&Arai, 1994]:

- The mounting process
- The feeding process
- The transporting process
- The transfer process

Depending on system borders the meaning of these above-mentioned processes can differ slightly.

3.3.1 Mounting process

The mounting process is the value-adding operation in the system. The mounting process attaches parts to an assembly. This can be done in several ways depending on the product structure, the stability of the assembly, the size of the assembly and so on. For automatic assembly it is important to have a stable base to start the assembly on. Therefore one should always strive towards a base-part assembly and if it is possible combine it with a sandwich principle, i.e. assembly in one direction preferable from above (vertical) [Boothroyd, 1992]. In FAA systems, the mounting process is predominantly performed by an industrial robot (IRb) using different gripping methods and often in co-operation with an active fixture that can be adjusted by a control system. Gripping and fixturing are sub-processes to the mounting process.

3.3.2 Feeding process

The feeding process is the process in which parts that are to be assembled are oriented and presented to the mounting process. The feeding process consists of four elemental functions [Makino&Arai, 1994]:

- | | |
|-----------|---------------|
| - Storage | - Orientation |
| - Feeding | - Escapement |

3. FLEXIBILITY AND KEY PROCESSES IN FLEXIBLE AUTOMATIC ASSEMBLY SYSTEMS

A more detailed definition of the feeding process functions is given by [Arnström et al., 1983]. In this definition, the feeding process consists of six fundamental functions, here in order of execution (storage excluded):

- | | |
|-----------------------|-------------------------|
| 1. Feeding | 2. Arrange in one plane |
| 3. Arrange in a queue | 4. Separation |
| 5. Orientation | 6. Escapement |

There are many feeding solutions on the market with varying solutions for these functions. There are, however, three main feeder principles [Arnström et al., 1983]:

- The functions are solved mechanically (typical vibratory bowl feeder)
- The orientation is made by the use of vision systems or advanced sensing after separation.
- The orientation is made before any other feeding function is executed. The orientation is made by the use of vision systems.

Feeding solutions tend to be very part specific, which in turn, means investment risks and need for large volumes. There are, therefore, needs for feeding solutions with more geometrical flexibility. By looking at the six fundamental feeding functions a modular approach can be taken to develop more flexible feeders [Arnström et al, 1983]. This has not yet occurred on a large scale.

3.3.3 Transport process

The transport process is defined as the process in which oriented parts and tools are transported within the assembly system [Makino&Arai, 1994]. Depending on how the feeding is solved, the transport process can be part of the feeding process. A very common way to decrease the space for part feeding is to present the parts on part trays. This means that most of the feeding process is done outside the assembly system. The transport process is then the process that presents the parts to the mounting process. In the case of part trays the transport process often makes use of conveyors or rotary tables. The conveyors are either free-flow or indexing while rotary tables are indexing. In some cases the transport is eliminated by having a “reversed material flow” where the mounting process is moved to the part pallet [Onori et al 1995].

3.3.4 Transfer process

The transfer process is defined as the process in which the ongoing assembly is transferred through the system [Makino&Arai, 1994]. The ongoing assembly is often referred to as the “workpiece”. The workpiece is a base-part onto which parts

are mounted. The transfer process also makes use of conveyors and rotary tables. The transfers are either free-flow or indexed.

Note that the given, and commonly accepted, classification of the assembly process is, according to the author not complete. To economically justify FAA-systems, products must, as much as possible, be designed based on the abilities of these systems. Therefore a more stringent classification of the sub-processes involved, and their relation to the design process and existing equipment, should be investigated [Tichem et al., 1999]. A well-structured approach to the assembly process may assist in the design process [Alsterman et al., 2001]. It will also improve the design flexibility as was discussed earlier by [Andreasen & Ahm, 1986].

In the next chapter some of the FAA systems found in literature will be described. The proposed solutions for the key processes, discussed previously, will be analysed. The various flexibilities discussed and defined above will also be analysed for each system

4 FLEXIBLE AUTOMATIC ASSEMBLY SOLUTIONS

This chapter intends to describe the FAA systems found in literature. The systems described in this chapter will be analysed according to the key processes and flexibility described in the previous chapter.

The thesis discusses FAA systems, in which Flexibility and Assembly are two of the main subjects within their title. Hence, the need to carefully study whether the known FAA systems to date have succeeded in forming an effective link between the required flexibility and required assembly processes. Therefore, this chapter attempts to describe and analyze the various solutions for the key processes and achieved flexibility, using the definitions discussed in the previous chapter. The description and analysis is performed in an effort to understand the connection, between the process solutions, and the achieved flexibility. An attempt is also made to present trends in process solutions and flexibility focus.

4.1 FAA systems described in literature

In this section FAA systems described in the literature are presented. Both industrial applications and academic projects are discussed. As the level of detail varies in literature the systems are presented accordingly. Systems for which the information could not be verified, or that are too roughly detailed are presented separately in the next section. The following systems are studied:

System	Organisation
Mark I	IVF/KTH, Sweden
Mark II	IVF/KTH, Sweden
Mark III	IVF/KTH, Sweden
SONY SMART concept	SONY, Japan
DIAC	Delft University of Technology, Netherlands
DRAS	The University of Texas, USA
FAS IBM Järfälla	IBM, Sweden
HIFAS	A Joint Venture project between German and Italian manufacturers.
Agile Manufacturing Workcell	Case Western Reserve University, USA

MAX

Fraunhofer Institute, Germany

DENSO Mobile Robot System DENSO

The above systems have been chosen because they all have somewhat different solutions on key processes and system layouts. Most of the systems are rather old but since the focus is on process solutions and flexibility achievements, and understanding the connection between these, the age of the systems is not all that important. Note that the automated process solutions are focused. Some of the systems do have manual assembly integrated but these will only be detailed very roughly.

4.1.1 Mark I (1984, KTH)

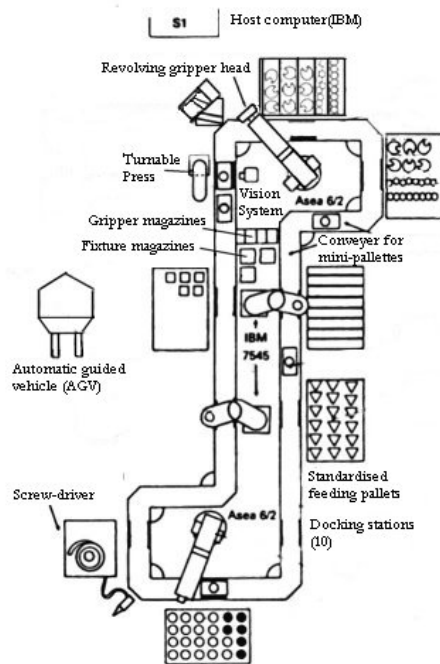


Figure 18.. A brief outline of the FAA system Mark I built in the laboratory at IVF/KTH. [Arnström & Gröndahl, 1985]. The picture is taken from a licentiate thesis. [Holmstedt 1989].

Mark I was initiated as a research project at KTH¹¹ in co-operation with IVF¹². The system was first presented in 1984 and detailed at the CIRP conference in

¹¹ The Royal Institute of Technology

¹² The Swedish Institute of Production Engineering Research

1985 [Arnström & Gröndahl, 1985]. The system was mainly built for the purpose of research and was therefore not intended for industrial use. The intention was to study two single FAA cells and the connection between these cells. According to the definition of FAA cell and FAA line in Figure 16 the Mark I system is in the grey-zone. It is here considered to be an FAA line, due to the important transfer process and the relatively few operations per IRb.

The objectives for the system were that it should run automatically during 2-3 shifts and concentrate the manual efforts to the day-shift. A prerequisite for this was, therefore, to separate the manual operations from the automated operations. It is not clear, however, if the manual operations were to be de-coupled both in time-of-day and tact-time. Manual operations meant mainly refilling of pallets, feeders etc. and not certain assembly operations. Another objective for the system was that it should be able to assemble different variants and /or products. In order to handle assemblies to order, instead of prognosis the system had to be able to run small batches. Small batches were in this project defined as a run-time less than 1 hour [Arnström & Gröndahl, 1985]. The system was to be used for products with short life-cycles.

To be able to achieve these objectives, the system was designed to have geometric-, routing- and volume flexibility. The system was also designed to have automatic:

- Set-up between batches
- Error recovery
- Materials handling and feeding

The key processes

The transfer plays a major role in the Mark I system as the system has four IRbs performing the actual assembly. The transfer process was performed by the use of a free-flow conveyor equipped with mini-pallets. The fixturing of the base-part was made possible by using part specific fixtures that were placed on the mini-pallets with a standard interface. The fixtures were docked to each FAA station and the assembly was performed on the conveyor. There were in total 10 docking stations along the conveyor.

The transport is done partly by an Automatic Guided Vehicle (AGV) that transports parts on standard pallets and docking them on to the different FAA stations. Some of the transport is made by product specific feeders attached to the FAA stations.

The feeding was partly carried out by special purpose feeders. Some of the feeding was performed manually by the system operators that put the parts “correct-

side-up” on pallets for vision-picking, or completely oriented in patterns for pallet picking.

The mounting was performed by four IRbs; two antropomorf 6-degree of-freedom(DOF) of the type Asea 6/2 and two SCARA IRbs type IBM 7545. The Asea IRbs had three working points along the transfer conveyor while the SCARA-IRbs had two each. The IRbs had changeable tooling using revolving gripper heads, exchangeable fingers or complete change of gripper by using an electromagnetic holder. Special purpose equipment could be docked to each FAA station.

Conclusions drawn by the project team were [Arnström & Gröndahl, 1985]:

- Use 6-DOF IRb to take advantage of different feeding techniques
- Simulate before building
- It is the number of components in a product that defines the necessary number of IRbs.
- Picking parts by the use of vision systems is possibly the most flexible way to solve the feeding problems
- Unbalanced lines should be accepted
- Use servo-controlled parallel jaw grippers to decrease total changing time.
- Insertion problems that need active/passive insertion techniques are not highly frequent.
- Error-recovery is needed in small batch assembly. Programmable sensors should be used and a knowledge-based diagnostic system could be necessary.
- It is essential to settle some kind of standard for computer communication

An analysis of the various flexibilities that are accomplished in this system can be done by identifying the various flexibilities described earlier in section 3.2 starting from high frequent changes to more long term issues as shown in Figure 43 page 129. As described earlier, the flexibility can be divided into dynamic flexibility and static flexibility.

Dynamic flexibility

The systems technical flexibilities are accomplished by using changeable grippers and “dockable” special purpose equipment, for example the screwdriver station and the press. The use of two 6-DOF IRbs further increases the operations possible.

The geometrical flexibility of the system is accomplished by special purpose part- or variant- specific fixtures that are attached to standardised mini-pallets. Changeable grippers or gripper fingers contribute further to the geometrical flexibility.

Routing flexibility as described before is the ability to handle changes by changing sequence of operations, batches or orders. The Mark I system has a rather low routing flexibility. If an assembly operation fails due to gripper failure the gripper can be changed if proper error-recovery software is implemented. Assembly sequences can be changed if the pallets are allowed to travel several laps through the system. There is however, no possibility to on-line re-route the assembly to another station. If a failure would occur on a fixture, the fixture cannot leave the system or be put “on hold “ but, instead, it will block other fixtures. If an order failure would occur, for instance a faulty or missing part, the system cannot re-route the pallets and start with another order while waiting for new parts. Since there is specific equipment at certain stations, and this equipment is not moveable on-line, another station cannot take-over an assembly. The different types of IRbs make this impossible even off-line.

Change-over flexibility is implemented in the system as the AGV moves new pallets into a docking station and an IBM 7545 SCARA-IRb unloads fixtures containing a finished batch and loads a new batch. The changeable grippers makes it possible to change between variants or products. The fixtures, must however, be prepared in advance, manually. The multiple assembly stations at each IRb makes it possible to have a certain overlap in time when changing between variants, i.e. one station can be prepared for the next variant during assembly.

Volume flexibility could be accomplished by dividing the system in half, i.e. letting the “*least common divisor*” do separate work. The “*least common divisor*” in this system seems to be an IBM-IRb and ABB-IRb with docking stations and grippers. In times with high volumes the system works as a true line with the whole system assembling one product. In times with low volumes the “least common divisors” are assembling separate products. This was, however, not intended/ detailed by the authors.

Static flexibility

Introducing a new variant into an assembly system means changes in, for instance, parts, number of parts, grippers, assembly sequence and fixturing. Variant flexibility means managing these changes without a severe penalty in cost and time. Variant flexibility means however that the changes are more or less planned for during system design and the changes have therefore often rather limited impact (or penalty). The variant flexibility for this system is accomplished by the use of docking stations for special equipment and changeable grippers. The fixtures are variant dependent but are attached to conveyor-specific mini-pallets through a stan-

dard interface. Parts, grippers, magazines and minor feeders are presented on standard pallets with automatic connection of air, communication signals and electricity. This means that any variant specific solution are decoupled from the main system, i.e. new variant solutions are limited to the standard pallets and do not affect the system as a whole.

Product flexibility is a true challenge to accomplish as it means introduction of unplanned new products or variants in the system. This often means totally new parts, tooling, fixturing, assembly sequence etc. Therefore, it is often an attempt to use product independent system solutions as much as possible. The system concept of Mark I with docking stations for parts, tooling, equipment etc. makes the system product independent to a limited degree. One conclusion from the Mark I project was that the number of parts in a product to a large extent decides the necessary amount of IRBs, due to the restricted handling area for each IRB [Arnström & Gröndahl, 1985]. This implies that the products that can be introduced into the system must have a maximum of ~20 parts (5 parts/IRB), that is of course, if the assembly is to be performed within “one lap”. It is possible to do a subassembly on one lap and the final assembly on the next lap. This makes it possible to change parts and equipment at the assembly stations. The lead-time, however, through the system will increase substantially. The size of the product and parts are of course restricted to the size of the conveyor pallets. Since the assembly fixtures have a standard interface to the conveyor mini-pallets, there is no need for any changes on the conveyor. Special grippers and equipment can be introduced on the docked pallets. Since there are two types of IRBs in the system the assembly sequence of a new product can be awesome. Imagine that there are 6 parts in a straight sequence that needs a 6 degree of freedom IRB. Then the assembly would have to travel several laps in order to be completed.

Capacity flexibility was defined earlier as the ability for a system to easily expand or contract its capacity limits. The easiest way to increase the capacity for Mark I is to put another system next to the old one and connect them with the AGV. The size of the stepwise increase/decrease of capacity would then be the problem since twice as much capacity may not be needed. The interest lies in the smallest capacity increase allowed by the Mark I and still maintain the system idea. As mentioned above “*the least common divisor*” in this system seems to be an IBM IRB and an ASEA IRB with docking stations and grippers. If one divides the system further it will come down to equipment level and one does not take advantage of the developed system knowledge and experience. Basically, it will be like starting over building a new system with new surprises.

Rebuild flexibility will depend more on the individual equipment’s suitability than on the system-concepts suitability. When the need for rebuild occur, the actual system concept can no longer accommodate the changes needed for the new product and the use of the least common divisor is not possible.

4.1.2 Mark II (1987, KTH-IVF)

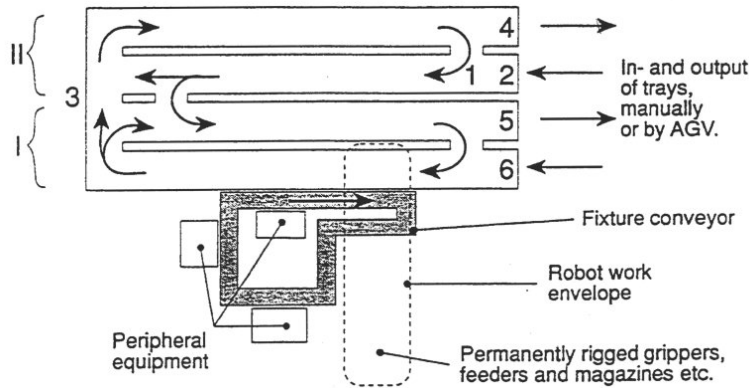


Figure 19. A brief outline of the Mark II system built in the IVF/KTH laboratory [Holmstedt, 1989] [Arnström & Gröndahl, 1988b].

The Mark II system was developed at KTH in co-operation with IVF. It was presented at the two conferences in 1988 ICAA [Arnström & Gröndahl, 1988a] and CIRP [Arnström & Gröndahl, 1988b]. The system was developed outgoing from the industrial trends that had emerged during that decade and these trends are still very much up to date. The system was developed to suit the production situation for industries in Sweden at that time:

- In Sweden the volumes for manufactured and assembled products are relatively small and...
- As capital tied in stock should be minimised there is a need for assembling small batches.
- The life-cycle for products decrease and the number of variants increase.

A goal with Mark II was to decrease the cost for an FAA system and make it more economical [Arnström & Gröndahl, 1988b].

The desired objectives of the Mark II system were:

- The capacity for the system should not be coupled to the number of parts in the product. The actual meaning of this is that the number of parts in the product should not decide the number of IRBs necessary to assemble the product.
- Since the system must be able to economically handle small batches the set-up time must be short. To achieve this it must be possible to quickly add and remove product specific equipment from the system.

- Due to the short product life cycle, new products must be easily introduced to the system without serious interruption of ongoing assemblies. This implies the need for off-line preparation of programs and equipment.
- In order to make the system economical the system must be able to perform an extended time automatically. This implies the need for automatic set-ups, error-recovery, feeding and of course assembly operations. This would raise the utilisation of the system.

In this FAA system a new assembly principle called the *sub-batch principle* was introduced[Arnström & Gröndahl, 1988b]. The batch was divided into sub-batches in which the same part was assembled to all base objects before changing to the next part, instead of the usual way where all parts are assembled to one base object before shifting to the next. The sub-batch principle reduces the time-loss due to gripper exchange, by dividing the gripper exchange time with the size of the sub-batch.

The actual working area in the system is small and the distance between part picking and mounting is short. This allows for short cycle times. Within the assembly system there are no balancing problems that reduce the utilisation of the IRb since the IRb is doing all the assembly tasks. In a larger perspective, however, there can be balancing problems since the actual system can be a bottleneck within a larger, total assembly system.

The key processes

In order to support the sub-batch principle a system layout was designed according to Figure 19. The system consists of two looped conveyors with the IRb in between.

The transfer process is carried out with a looped conveyor for the fixtures carrying base-objects. The conveyor is looped in order to accommodate the sub batch assembly. Each lap represents one assembled part. There is only one pallet in assembly position at a time.

The transport process also consists of a conveyor system for pallets, carrying parts. The parts are presented on a “part train” where the orders of pallets are arranged according to the assembly sequence of the product/batch. Product-specific equipment is transported into the system, i.e. grippers and fixtures, on the first pallet in the train during set-up and is placed in position by the IRb. At the end of the train the finished products are transported out of the system.

Feeding is performed by the use of pallets. Depending on the stability of the part the parts are oriented and separated on the pallet or oriented by the use of a vision system. During vision-guided picking the parts are only presented “right-side-up” on the pallet, not oriented.

Mounting is performed by one single IRb. The IRb is an ASEA 1000/2 hanging on a track that makes it possible to move the IRb 2.5m between the two conveyor loops. The IRb has exchangeable grippers by the use of an electromagnetic gripper exchange system. The IRbs working space is divided into three areas, depending on the frequency of the events in that area. High frequent events, such as assembly operations are placed in the area that give the smallest move thereby shortening cycle times. Less frequent events are then placed outside this area.

Dynamic flexibility

The technical flexibility in the Mark II system is accomplished by the use of changeable grippers and tools. Grippers and tools that need air supply or electricity can be placed in the working area of the IRb. New operations can thereby be added by adding tools permanently in the working area or attach them to the part train as explained above.

Geometrical flexibility is achieved by the use of moulded fixtures and changeable grippers. Parts presented on pallets and picked by the vision system increase the geometrical flexibility of the system.

Routing flexibility is needed when there is a need for changing operation sequence, changing batch or changing orders due to ordinary circumstances or failures. The Mark II system has a potentially good routing flexibility if everything works as intended. The system can change operational sequence if the assembly permits it, all that is needed is to change the order on the part pallets and change the IRb execution. It is, however, not clear whether this is possible without manual interaction. Changing batch is possible automatically. It means changing part train and moving the finished products out of the system. Changing between different orders could mean changing the whole set-up, i.e. changing fixtures, parts and grippers. The system layout seems to be able to accomplish this with the right software and sensors. Re-routing due to failure seems to be possible also.

Change-over flexibility between known variants are implemented in Mark II. Since all the necessary equipment for a certain product or variant is attached to the part train during set-up, the change over flexibility should be possible if software and sensors allow it. There is much to do in order to improve the sensors [Holmstedt, 1989]. There is, however, a large dependency between parts, fixtures and grippers since all of these are dependent on the "train". It is therefore not possible to do the change-over in parallel with the ongoing assembly.

The volume flexibility is not so good. Since all equipment in the system is unique the system has no "*least common divisor*" in that sense that part of the system can assemble another product. The only way to decrease volume is to lower the assembly speed. The other way around, to increase the volume requires an identical

system to be built, which is a question of capacity flexibility rather than volume flexibility.

Static flexibility

Variant flexibility is rather high in the Mark II system. The use of polyurethane moulded fixtures and, in some cases, part pallets increases the systems product independence, as there is a clear interface between standard equipment and product specific equipment. The use of the vision system makes it possible to decrease the costs for special feeders. Special feeders would in this case spoil the system idea.

Introducing a new product into the system means new fixtures, new tooling and to some extent new part trays. The moulded fixtures and part pallets facilitates the introduction of a new product. The product size and the stability of the assembly are limiting factors. The product flexibility is rather high in the Mark II-system on the behalf of the physical layout.

A totally new system has to be built in order to expand the capacity in this system and at the same time keep the system concept. There is no smaller part of the system that can be used to stepwise increase the systems capacity. To add another IRb would spoil the intention of the system.

The rebuild flexibility for this system is hard to determine. The conveyors can probably be used. Furthermore, the vision-guided picking and moulded fixtures could also be used in another system concept.

4.1.3 Mark III (1994, KTH-IVF)

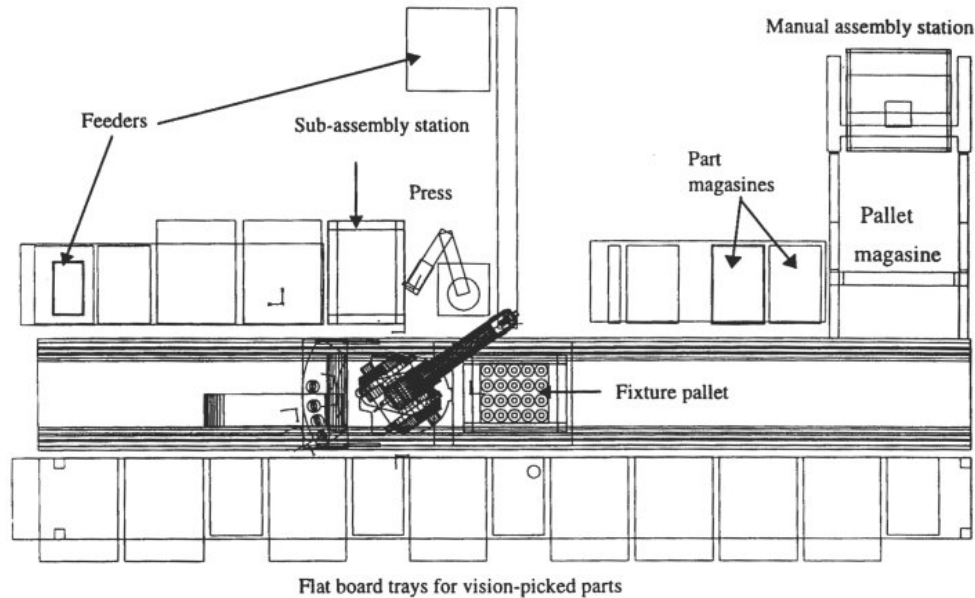


Figure 20. Mark III an FAA system built in the laboratory at IVF/KTH. [Onori et al., 1997].

Mark III is a research system built at KTH in co-operation with IVF. The concept was intended to be a complement to, and a further evolution of the previous described system concept Mark II. A further review of the requirements that should be posed on an FAA system in order to increase and facilitate the use of FAA added the following requirements to the requirements that was posed on the Mark II system [Onori et al., 1995]. The system should:

- Facilitate stepwise automation
- Allow for co-existence of manual and automatic operations
- Handle many types of products/variants
- Allow for different feeding solutions
- Have as large capacity span as possible
- Exploit an easy and low cost programming solution.

Mark III has kept the sub-batch principle from the Mark II system [Arnström & Gröndahl, 1988b]. Apart from that, some changes had to be made to the key processes in the system in order to handle the requirements posed on the system. A manual assembly station is integrated in the system to handle assembly opera-

tions that are difficult to automate or assembly operations that will be automated later(stepwise automation).

The key processes

The transfer process in the system is performed by the IRb itself. The IRb is placed on a rail and can be moved between different assembly positions along the rail. The system uses thereby a “reversed material flow” [Onori et al., 1997]. The IRb carries a pallet with fixtures, representing the sub-batch size, in a tray in front of it. As the assembly proceeds, the IRb moves to the position where the correct part resides. Empty pallets with fixtures or finished assemblies are exchanged through a pallet magazine. In cases where the assembly is a sub-assembly, the fixture can be placed as a part pallet along the track. If parts for some reason are not available or an express order has to be done the fixture pallet can be “put-on-hold” while continuing with the next fixture pallet.

The system allows many different feeding solutions from conventional vibratory bowl feeders to parts placed right side up on pallets picked by vision. The vision system allows for simple and low cost feeding solutions. Due to vision picking most of the transport process is eliminated or done outside the system.

The mounting process is performed by the IRb using part specific grippers. Gripper-exchange losses are reduced by using the sub-batch principle. Grippers are exchanged while the IRb moves to the next position along the rail thus reducing the losses due to travelling. Mark III introduces a decoupled manual assembly station to handle assembly operations difficult to automate technically or due to economical reasons where the operations are automated step by step as solutions can be found for the specific operation.

Dynamic flexibility

It is possible to have a high technical flexibility in the Mark III system. The moving IRb makes it possible to have specific tooling and equipment along the rail close to the parts concerned. An example of this is the pressing equipment that was installed in the system.

The possibility to handle parts with different shapes is rather high due to the many ways parts can be presented to the IRb. The vision system and the possibilities to change grippers increases the geometrical flexibility. However, when using the vision system much of the orientation of unstable parts has to be done manually by the operator, (putting parts “right-side- up” on pallets with part specific fixtures).

The routing flexibility is very high in this system. The routing is uncomplicated physically and there is no dependency between parts, i.e. the parts do not have to

be routed in a specific order. In fact, there is no automatic part routing involved. It is only fixture trays that are moved around in the system during re-routing.

Change-over flexibility is also rather high due to the uncomplicated routing in the system. New parts can be put along the rail during assembly, which makes it possible to prepare the change-over in parallel with on-going operations. The change of fixture tray is done without severe time-loss. New grippers can, however, be a problem in cases when the grippers attached to the IRb vehicle have to be changed.

Volume flexibility is not so good in the Mark III system since there are only one IRb. There is no "*least common divisor*" in the system that can work separately in parallel and assemble different products or variants (or orders). There are no assembly systems within the assembly system so to speak. There is, of course, possible to involve the manual station more frequently, but since this study is focused on the automated systems volume flexibility it is not relevant. There is always possible to have a manual alternative when the product allows it.

Static flexibility

The product flexibility and the variant flexibility in particular are good. The many feeding solutions and the fact that the IRb has an extra degree of freedom along the track makes it possible to add new products along the track without disturbing the ongoing assembly. The penalty for change is thereby reduced. The length of the track may be a limiting factor though. To avoid time loss due to long travels the product must be gathered to a certain area along the track. The loss due to travel is dependent on the size of the sub-batch [Arnström et al., 1993]. New equipment can also be placed along the track. If the assembly size admits it, the fixtures can be placed on standardised trays and thereby quickly be introduced.

Capacity flexibility is achieved in this system by adding or removing IRb from the track [Arnström et al., 1993]. The IRb's are then assigned separate working areas along the track and can co-operate through common areas where fixture pallets can be exchanged. When using two IRb's the location of equipment and parts along the track is essential. A strict serial assembly requires parts and equipment to be placed along the rail, according to assembly sequence, so that each IRb has it available. There will be an intricate problem to place the manual station along the track. A parallel assembly requires duplicate part positions and equipment along the track, which is almost equal to a duplication of the system.

Most of the equipment in the system is not product specific which should make it possible to use the separate system components in a new system concept.

4.1.4 Sony's Smart Concept (1991, Sony)

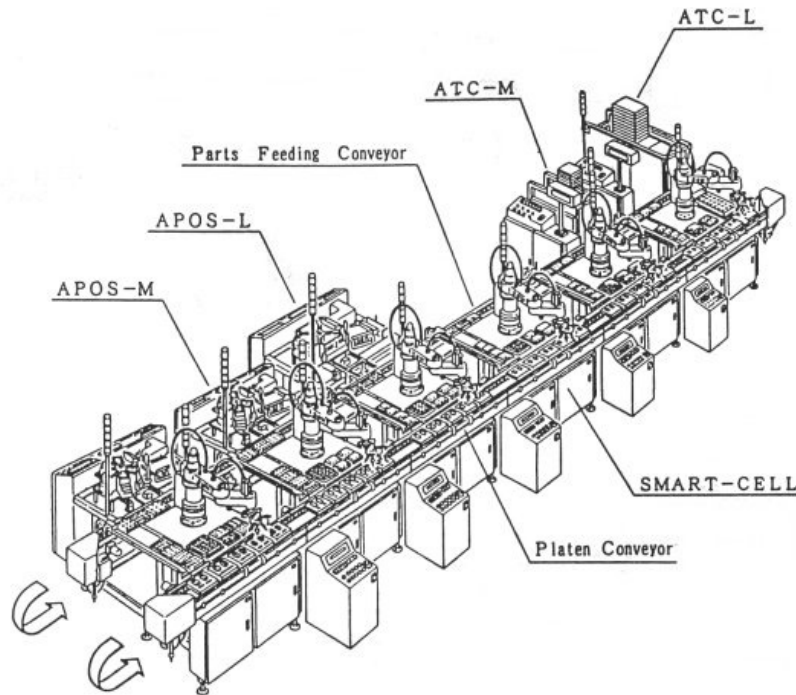


Figure 21. The Sony SMART system [Kimura, 1991].

The research and development of the first SMART system began in Japan 1983. The system was supposed to assemble components for Sony's 8mm VCR. The goal was to develop an assembly system with a limited pay-off time for a limited quantity of production (60000/month at 24 h operation) [Kimura, 1991]. The development emerged from the belief that it is possible to create systems that are optimal for a broader application level, i.e. not focusing on a target volume and target product. "...it can be said that there must be an optimum system for each target of assembly and each volume of production. However if we hold this belief, then there cannot be an universal machine for assembly" [Kimura,1991].

The SMART system can be considered as a small FAA station that, in several units, can be configured into a line. Each FAA station assembles a maximum of 6 parts. The system was designed with the idea that an FAA station should assemble several components.

The following requirements were considered during development, [Fujimori, 1990]:

- Investment-efficient Small-lot Production (full utilisation of robots)
- Efficient Component Supply (universality in component supply)
- High Flexibility (Changes in product and processes)
- Less restrictions to product design (Meet the needs of design)

It must be made clear that there are differences in Japan and Swedish industries definition of what small-lot production is. In Japan, a product that runs for 1 million in 6 months is considered a small volume, while in Sweden this would be considered a high volume product.

Key processes

The transfer is performed by the use of fixtures on a conveyor in front of the IRb. The fixture pallet stops on the conveyor during assembly and is thereafter moved to the next FAA station, Figure 21. The conveyor seems to be of “free-flow” type and can act as a buffer between stations.

Transport of parts is done on polyurethane foamed pallets on a conveyor at the rear side of the FAA station. A specially developed device called ATC-M is used to change part pallets on the part conveyor, i.e collect empty pallets and add re-filled ones. In cases where parts are too large to handle by the part conveyor a special device named ATC-L is docked directly to the station [Kimura, 1991].

The feeding process was specifically focused upon the development of the SMART-system. *“Even if robots exhibit a high level of flexibility, the amount of flexibility that can be achieved depends to a great extent to on how much universality the system has for component supply”* [Fujimori, 1990].

As an effort to create an efficient component supply, the APOS system was developed. Parts are oriented by the use of part specific pallets. The pallets are made with foamed cavities that fit the parts in only one way. The pallets are then tilted and applied a 3-dimensional vibration mode, which is also specific for the part. When parts then are “poured” over the tray they are aligned into the cavities.

Mounting is performed by a SCARA-IRb. To reduce gripper exchange time the IRb is equipped with a special designed turret head with six tools that can be indexed to assembly position. In order to keep the tool light the indexing mecha-

nism is integrated with the IRbs roll axis [Fujimori, 1990]. Internal and external gripping is used.

Dynamic flexibility

Technical flexibility is rather limited in this system since the FAA station is optimised to assemble six parts. Due to the limited space in the station there is no room for additional tooling. The revolver gripper limits the number of grippers possible to use. The six grippers are designed to handle many different components. In order to increase the geometrical flexibility (or independence of geometry) internal gripping is used. Standardised holes on the parts partially compensate for the system's limited geometrical flexibility.

Routing flexibility is low in the SMART system. On-line re-routing due to planned changes or unexpected failures is not implemented. If a failure appears in one station the others will soon be stopped if no manual correction is performed. Part routing is good while fixture re-routing is poor and tool routing infinite.

Change-over flexibility is not focused. Instead the focus is more on variant or product flexibility. Therefore, the change-over abilities between planned variants is rather limited. Change-over between variants or products means new fixtures parts and tools. To have an effective change-over these changes should be able to be done in parallel with the last ongoing assembly for the previous variant or product. This is not possible in the SMART-system

Volume flexibility is the ability to vary the output between the systems capacity limits. The only way to do this in the Smart system is to lower the assembly speed. Because of the limited tooling for each station and the fact that the assembly is performed on the fixture conveyor, making it impossible for other fixtures to pass, it is not possible to divide the system into "mini-systems" that can assemble different variants in parallel

Static Flexibility

Variant flexibility is rather high in this system. Overall, it seems like the development of the system has focused more on static flexibility than dynamic flexibility. The system concept focuses on parts presented on trays. Since variants and products are planned for, the implementation should not be a problem. New fixtures, however, as well as parts and tools must be designed appropriately.

Product flexibility is high in a certain product range (size, weight etc). The coupling between number of parts and number of stations could, however, be a problem. New products or variants (not planned for) means, often, new tools, new fixtures and new parts. In turn, this could affect the key processes. It is not

possible to easily add new solutions to a key process, which decrease the product flexibility.

Capacity flexibility is high. There is a clear focus on this in the system concept: Small identical FAA stations that can be connected to each other as capacity increase. The “*least common divisor*” is obvious in this system concept. However, the limited tooling in each station demands at least three stations for an ordinary final assembly.

4.1.5 DIAC (1991, TU Delft)

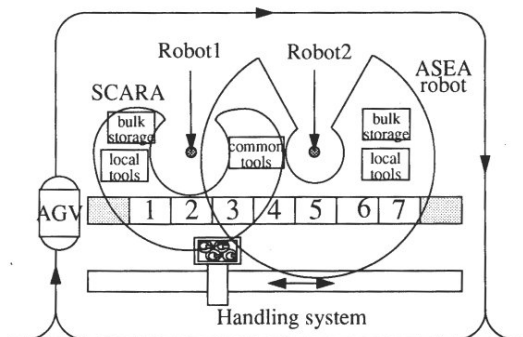


Figure 22. A rough outline of the DIAC assembly system [Willemse, 1997], the picture is a renewal of the original by [Meijer & Jonker, 1991].

DIAC (Delft Intelligent Assembly Cell) is a system developed at Delft University of Technology. The goal for DIAC was to develop an intelligent flexible assembly cell within four years, showing its feasibility by demonstration of successful assembly of several industrial products [Willemse, 1997].

The products that was focused had the following Production profile: [Meijer & Jonker, 1991], [Willemse, 1997]:

- Make-to-order assembly
- 10 000 – 100 000 annual volume
- Approximately 20-30 parts, each not exceeding 1 kg
- The size of the product fits within a cube of 200mm and weighs less than 5 kg
- 10-100 variants in one product family

Despite the achievements in individual areas within the system such as assembly planning, IRb control, vision systems etc. the goal to realise a generic flexible

automated assembly system has not been achieved [Willemse, 1997]. However it is still interesting to study the system layout and the key process solutions and discuss what kind of flexibility that can be achieved.

Key processes

The transfer process is executed by moving the assembled product on trays. The trays are moved within the system by a specially developed robot on a rail. The system is called the TTT handling system. Product-, part- and tool trays can be positioned in a 24-positioned random access buffer. The buffer can be seen as a shelf with 24 tray positions. The mounting is performed on top of the shelf. Tools, parts and product are handled by the TTT-system. In this way, the transfer process and transport process are integrated (and coupled). Parts, tools and products are taken in or out of the system by an AGV. Large emphasis has been put on the transport and transfer system, since it has a substantial influence on the assembly efficiency [Storm & Boneschanscher, 1991].

The parts are presented to the mounting process in “semi-ordered” fashion, i.e. the parts are presented on trays, separated and with “correct side up”. The final orientation is made by the use of vision. The trays have pegs to avoid that parts overlap and thereby obstruct the part identification.

Mounting is performed by two IRBs that partly share the workspace. The IRBs can, to a certain extent, share tools, parts and products and co-operate. There are two types of IRBs: one SCARA IRB with 4 degrees of freedom and an anthropomorphic 6 degree of freedom ASEA IRB. Some advanced tooling is used that uses transputers that calculate appropriate ways to grip a part.

Dynamic flexibility

Technical flexibility depends on the availability of tools and other equipment for the IRB. The use of two IRBs increases the technical flexibility since they are potentially good in different aspects. Assembly on trays can however jeopardise the assembly stability and exclude possible assembly operations. Geometrical flexibility depends on available tooling and the IRB's degree of freedom. The geometrical flexibility should be high if the advanced tooling works as intended.

If the assemblies are stable (not jeopardised during transfer) the routing possibilities are high in this system. There is no dependency during assembly due to the random buffer access. Tools, parts and fixtures do not have to be routed in a specific order. It is, however, not possible to do routing of tools parts and fixtures in parallel.

Change-over means changing of tools, parts and fixtures, preferable in parallel with ongoing assembly to save time. The TTT-system and the AGV can work in

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parallel with the ongoing assembly and change parts and tools in the buffers. The system principle seems to have a rather high change-over flexibility if the control system can handle it.

Volume flexibility in this system depends on whether the two IRBs can work on separate products or variants in parallel. This depends largely on the product since the SCARA IRb can assemble vertically only. The tooling must be separate for each IRb to avoid deadlocks. It is of course always possible to run the system at a lower pace but this is not optimal.

Static Flexibility

Adding a planned, new variant means new parts, new tools and perhaps new fixtures. Since fixtures and tools and parts are planned for, they will most likely fit into the existing system concept. Limiting factors are size of tools, parts according to specification above, and stability of assembly. Variant flexibility is good

Product flexibility is however not so good. Adding not planned products or variants may be problematic due to the limited size in the random access buffer. Adding new not planned products may incorporate new key process solutions and the system concept may not support this.

Capacity flexibility for the system is rather low. However, it is possible to put another IRb next to the existing ones, thus adding more storage places to the random access buffer and extend the track for the TTT-system. There is, however, a limit to how many IRBs the TTT-system can serve.

4.1.6 The DRAS system (1993, UoT)

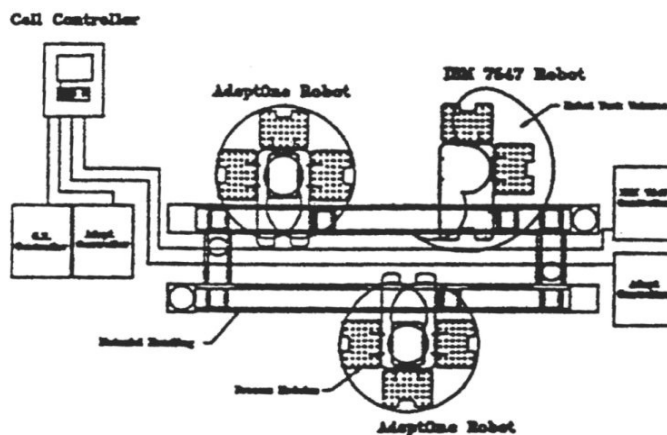


Figure 23. The DRAS system [Mills et al., 1993].

The DRAS (Dynamically Reconfigurable Assembly System) project started out in the late 80's at the Automation & Robotics Research Institute: The University of Texas at Arlington.

*“ Since its inception in 1989, the main purpose of Dynamically Reconfigurable Assembly System (DRAS) has been to advance the state of the art in flexible assembly through applied research and prototyping activities of direct relevance and use to our industrial customers ”*¹³.

The decreasing product life-cycles and the decreasing lot-sizes urged for another way to develop assembly systems for the industry. The project team foresaw that product tailored systems could no longer be economically justified. The research therefore focused on developing a system that could easily be reconfigured to new circumstances as products changed. The main effort was to isolate product specific system features that change frequently, from the system's core infrastructure, which varies little from application to application.

During development, four basic principles were used [Mills et al., 1993]:

- Layered architecture.
- Hybrid top-down/ bottom-up system development.
- Separation of functionality from control. (A similar approach was also introduced by Nyström at KTH [Nyström, 1992]).
- Object-oriented constructs in the software.

The layered architecture approach divide the hardware, information and functional software into three layers. The *base*-, *process* and *product* layer. It is an analogy with the ISO/OSI model for computer communication. One of the purposes of the layering is that a change in one layer should not affect a layer below, i.e. changes in a process should not affect the base system. This can be seen as a way to de-couple product specific system solutions from solutions that are necessary for any system. The base system consists of generic manufacturing and information resources, such as flexible manipulators, material handling, working surfaces, air supply and so on. The process level consists of the process specific hardware and logical building blocks that can be added to the base system. The capability of the base system and the process building blocks determines the functional capabilities of the system [Mills et al., 1993]. The product layer consists of product based information that determines which processes and productions sequences that are required to assemble a certain product.

¹³ Quoted from the Automation & Robotics Research Institute's homepage. A department of the College of Engineering at The University of Texas at Arlington on Riverbend Campus.

The hybrid top-down/bottom up system development means that the system is not merely developed outgoing from the product itself but the system itself provides guidelines by providing “building blocks”. In this way it is possible to reduce the precise product-tailored systems and make them more general [Mills et al., 1993].

Separation of function and control is an approach more focused on the control software where one tries to de-couple the function (task) from the control of the execution of the function (task). Very much like the FACE control system in the MARK III system [Arnström et al., 1993], [Ericsson, 1996].

The object-oriented principle is used in both software and hardware using the characteristics modularity, hierarchy, inheritance and so on.

Key processes

There is very little described about the physical system that is implemented outgoing from the above-described principles. It is therefore hard to analyse it, but an effort to discuss the various key processes is given below. The discussion is based on the test system in Figure 23.

The transfer process is incorporated by the use of a conveyor system. It is part of the base system described above. Pallets are used with a standardised interface to fixtures. It is proposed that the conveyor system should be modular to allow the system to grow by extending the length of the conveyor.

Mounting is performed by IRbs. In the test system two Adept IRbs and one SCARA IBM7545 is used. The IRbs are mounted on a small table designed to take a wide range of different IRbs. The table is designed in a way that when the IRb is attached to the table it is considered a base system module. The table also has a space for end-effectors (gripper, tools). “*Modular end-of-arm tooling is a critical support for the development of reconfigurable and extendible generic robot workstations*” [Mills et al., 1993].

Transport and feeding are not detailed in the literature. However, it seems like the process modules will take care of this. The process module consists of two sub-modules: the process module itself and the process attached to it. The process modules will handle feeding and transport of parts and assembly processes. These modules have to be easily attached and detached to the IRb base system module. Standard interface plates carrying air and signals are used to facilitate this. The process modules are work surfaces around the IRb-module, each IRb carrying more than one process module. The process module is equipped with wheels and standard interface plates so that the module can easily be moved around in the system.

Dynamic flexibility

It is hard to analyse the dynamic flexibility issues due to the limited explanation of the system's on-line abilities in literature. However, some assumptions can be made based on information from the literature and the study of the test system layout.

Technical flexibility depends on the systems ability to present appropriate tooling (grippers, end-effectors) to the IRb. In other words, does the system support on-line changes of grippers? Some tooling can be placed in reach of the IRb permanently but that is rarely sufficient in FAA systems. There must be a possibility to change tooling during assembly if the product demands more tooling. The DRAS system has therefore a rather low technical flexibility since the system has to be stopped in order to add tooling change tooling. Geometrical flexibility depends largely on the tooling available for the IRb and the IRb's degree-of freedom. The DRAS system can be configured with different types of IRb's but the tooling is a limitation.

Routing flexibility is low in this system since the only thing that is routed is the on going assembly on the conveyor. The system example in Figure 23 allows for change in assembly sequence by letting the fixtures circulate around the track until assembly is finished. However, there can be no change of operations between IRb's due to no routing possibilities of parts and tooling.

Change over flexibility is very low due to the above-mentioned limitations of routing. Change-over flexibility means changes of fixtures, tooling and parts. This can not be accomplished on-line.

Some amount of volume flexibility is possible to achieve since the different IRb's to a certain extent can work on different products and thereby do assemblies in parallel. The limited space around each IRb makes it however difficult make a sufficient amount of different parts available.

Static flexibility

The static flexibility is more focused in this system concept. The approach with standardised modules with standardised interfaces makes it possible to easily re-configure and rebuild to other applications. The variant flexibility should be quite good since the variants are planned for and modules can be configured in advance before added to the system.

Product flexibility means that some key processes may have to be changed. The layered system architecture may facilitate the configuration necessary. Unplanned products and variants can be configured on modules in parallel with ongoing assembly.

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Capacity flexibility is as discussed before the ability to increase the system by the “least common divisor “ and thereby stepwise add capacity. Capacity flexibility can perhaps be measured as the size of the “least common divisor”. The smaller “*least common divisor*” the better capacity flexibility. In the DRAS system it seems to be a rather high capacity flexibility.

Rebuild flexibility is high if the system idea and concept can be fully implemented.

4.1.7 IBM Järfälla FAA system (1986, IBM)

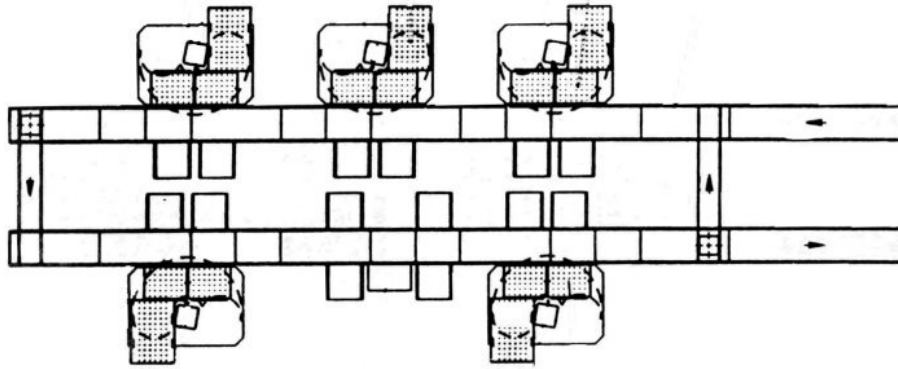


Figure 24. The FAA system at IBM Järfälla [Holmstedt, 1989].

In 1986 IBM presented an FAA system called FAS (Flexible Assembly System). The system was built in Järfälla outside Stockholm, Sweden. The purpose for the system was to assemble the printer head for IBM's printer 4234. The system consists of 5 automatic assembly cells and a one manual station. The manual station loads assemblies on pallets and assembles some tricky parts before shifting out the pallet on the conveyor which connects the assembly cells. The assembly is divided between the cells so FAS-system is a line consisting of FAA stations.

Key processes

Transfer is performed by the use of a conveyor. The assemblies are placed on pallets 18 per pallets. Assemblies are fetched from the pallet and put into a fixture

at each cell before assembly, i.e. the assembly is not transferred through the system in the same fixture.

There are no separate transports of oriented parts in the system, instead this is made outside the system and as a part of the feeding process. Vibratory bowl feeders and different types of magazines are used to present parts to the IRb. Some special tooling is used to apply e.g. glue.

The mounting process makes use of IRb's of the type SCARA. It is IBM's own IRb 7545 that is used. Gripper exchange is made possible by gripping other tools and grippers with a fixed pair of fingers mounted on the IRb.

Dynamic flexibility

Technical/geometrical flexibility depends largely on how well the presentation of tools to the IRb can be performed. In the FAS system there are no routing abilities for the tools which means that only the tools that fits in the workspace can be used. Geometrical flexibility depends also on the feeding solutions of parts. The FAS system uses various types of part specific feeders which decreases the geometrical flexibility.

Routing flexibility is low in this system. The only thing that can be routed is the pallet with the assembly. Tools grippers and fixtures cannot be routed. The assembly cannot be routed to another station along the line in case of a failure.

Change-over flexibility is low the system is configured for one specific product and assembles only that product.

Volume flexibility is low in that sense that different variants cannot be assembled in parallel. At least at current configuration.

Static flexibility

Variant flexibility should be rather high since the system is, in a way, modularised and one module can be used to phase-in and test new variants in parallel with ongoing assembly.

Product flexibility is rather low since the system is dedicated to the products it is planned for.

Capacity flexibility is high since the "*least common divisor*" is obvious and these stations can be added along the line if a capacity increase is needed.

4.2 other systems in literature

Due to a limited system description in literature the systems below are described briefly. Flexibility issues and key processes are difficult to have an opinion about.

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The systems are often described with a narrow focus to some problem area within automatic assembly systems.

4.2.1 HIFAS (1988, Piaggio)

The HIFAS (Highly Flexible Assembly System) project was initiated in 1988 as a joint venture between German and Italian manufacturers. The purpose for the project was to develop a flexible assembly system where fast changeover between variants and different products where possible. The project resulted in two assembly lines, one for the assembly of moped engines and one for assembling a starting mechanism for power saws. The system's degree of automation ranges from manual assembly to total automatic assembly. The system is built as a conventional line where the assembly is transferred through the system on fixtures or pallets and docked to stations along the line.

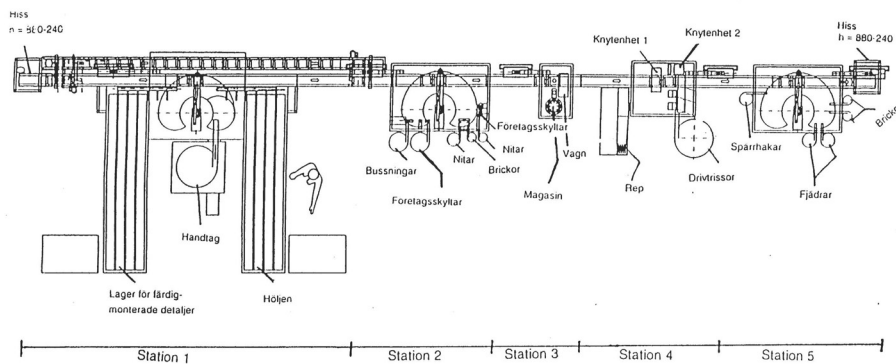


Figure 25. The HIFAS system.

4.2.2 Agile Manufacturing workcell (1996, CWR)

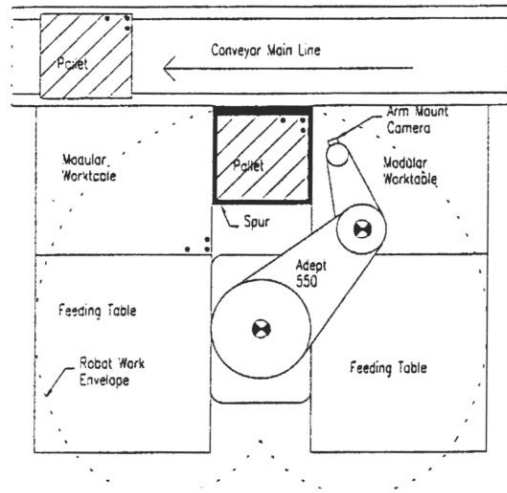


Figure 26. The Agile Manufacturing Workcell.

The Agile Manufacturing Workcell (AMW) is a system concept introduced at the Case Western Reserve University in Cleveland Ohio, USA [Quinn et al., 1996] [Quinn et al., 1995]. Agility has been defined differently in the research communities. Here the meaning of agile manufacturing is equal or similar to this thesis definition of product flexibility or perhaps variant flexibility. Agile manufacturing is here defined as, “...the ability to accomplish rapid change-over from one product to the assembly of another product” [Quinn et al., 1996]. It is not clear whether the change-over is between products planned for or totally new unplanned products.

The system has a modular approach similar to the DRAS system described earlier. Transfer of assembly is performed on a conveyor by the use of pallets. The feeding solution is solved through a special arrangement with three conveyors and a vision system, Figure 27. Mounting is performed by an Adept IRb, SCARA type. Each IRb is surrounded by two modular removable worktables and two fixed feeding tables. The exchangeable tables allows specific hardware to be easily placed within the IRb work envelope.

4. FLEXIBLE AUTOMATIC ASSEMBLY SOLUTIONS

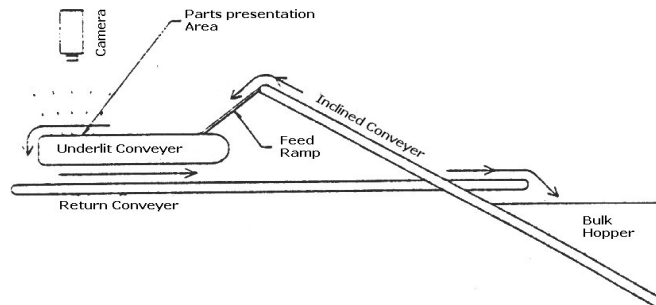


Figure 27. Flexible parts feeder in AMW [Quinn et al., 1996]

A goal for the system is change-over between products with minimum of change in tooling and software. The flexibility focus seems to be placed more on the static flexibility issues than Dynamic flexibility, i.e. variant flexibility and product flexibility is focused.

4.2.3 MAX (1993, IPA)

The MAX system (Modular Assembly eXample) is a system brought up at the Fraunhofer Institute for Manufacturing Engineering and Automation [Schweizer & Grau, 1993]. The system has a focus on jointing technology where special tooling has been developed for clinching, insertion and ultrasonic welding. The system consists of five IRbs, four which are connected with a conveyor. One of the IRbs are hanging on a rail above the system. The IRb has thereby an 7th axis similar to the MARK III system described above. The hanging IRb can assist in assembly operations or act as an alternative material flow system. The system is also an experimental system to test control systems.

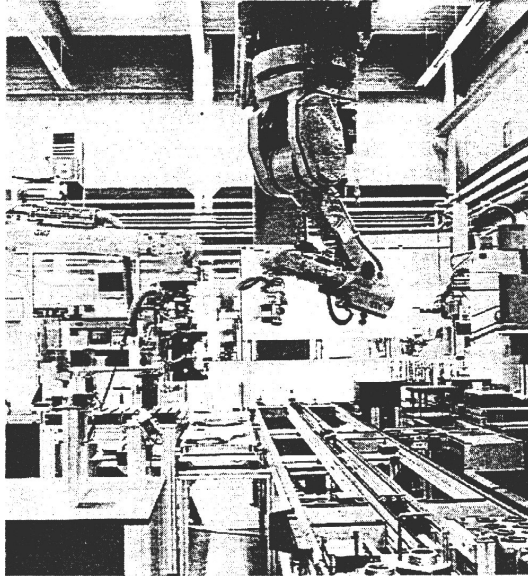


Figure 28. The MAX-system [Schweizer & Grau, 1993].

4.2.4 DENSO Mobile Robot System (1998, Denso)

Denso Mobile Robot System is a production system that tries to cope with the production volume fluctuations by copying the human behaviour in manual assembly systems. In this way one hopes to increase the economical efficiency of the system for a large volume range, contrary to traditional systems that have a narrow volume range in which the system is economically efficient [Hanai et al., 2001]. Denso introduced seven of the mobile robots into the starter assembly line at its Anjo plant in May 1998.

The system consists of a traditional transfer line where pallets with assemblies are transferred through the system. Process stations are placed along the line. Parts are fed to each process station by general part feeding units. The assembly is performed by IRb placed on guided vehicles. Parts are oriented by the use of a vision system. The IRbs can co-operate when needed. Each IRb can freely travel to any process station along the line. As volume fluctuates the capacity can be increased/decreased by adding/removing IRbs by the increment of one.

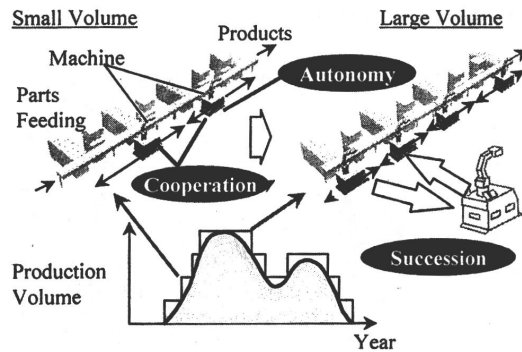


Figure 29. The DENSO system concept.

This system focuses on the value-adder in the assembly system. As volume increases, the only thing that is added is IRBs. This system has its focus on static flexibility, e.g. capacity flexibility.

4.2.5 HIPS (Human Integrated Production System)

HIPS is a Eureka project, EU-1060 FAMOS-HIPS, involving system vendors, universities and manufacturers (GWS, Nokia, Festo, Pirkkala University of Technology and others...). The purpose of the project is to develop an assembly system solution that can cope with a constantly change in products and product volumes and thereby help plant managers to protect long-term investments, [Heilala & Voho, 2001].

The system has its focus within light-weight assembly and uses a semi-automatic approach. *“For reconfigurability and agility, the best approach is the modular semi-automatic approach by combining flexible automation and human skills”*[Heilala & Voho, 2001]. It combines automated and manual workstations with an automatic material flow.

The transfer process is performed with pallets and modular conveyors. Pallets are equipped with “intelligence” in the way that each pallet has a escort memory attached to it. The memory provides the control system with product specific information.

Transport and feeding is also performed by the use of pallets. The parts for a specific product are collected onto a pallet and routed on conveyors to an appropriate workstation or several workstations if assembled in serial, [Heilala & Voho, 1997].

The problems concerning automation of the mounting process is not focused. Instead, the mounting is mainly performed manually and facilitated by the use of a interactive task support system [Heilala & Voho, 1997]. Due to the manual

mounting, the system is without saying very flexible in the high frequent events. Since technical- and geometrical flexibility depends mainly on the mounting process these flexibilities are high. The “intelligent” pallet and distributed control makes the routing flexibility high. Due to manual mounting the change-over flexibility is high. One could say that in general due to the manual mounting most of the flexibility types, described in section 3.2.2, are higher than in a total automatic system. This system is therefore a little outside focus for this thesis, however, the intelligent pallet and the modular conveyor system are two approaches that are important for the future development of FAA.

4.3 Concluding discussion

This chapter has focused on FAA systems described in literature. One should be aware of that there are other systems that are not described in this thesis. The reasons for not describing all systems are that, the system approach is focused on something not focused in this thesis, or that, the author has not been aware of its existence, or the system adds no new input to what is already known. Below are a summary and a discussion concerning trends in key process solutions and flexibility focus. A summary of each system concepts contribution is also presented.

4.3.1 Key process solutions a summary

In Table 6 is a summary of the key process solutions for each system described earlier. The predominant transfer solution is the use of conveyor and pallets. One can clearly see a more frequent use of vision systems to create part-independent feeding solutions. Modular system concepts are also emerging in order to handle change. Some systems, like the DIAC and MAX, focus on developing flexible joining techniques. Overall the focus is to find product independent solutions.

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Table 6. Summary of described systems key processes.

	Process			
System	Transfer	Transport	Feeding	Mounting
Mark I	Looped free-flow conveyor with pallets carrying exchangeable part specific fixtures.	Pallets transported by AGV. By traditional feeders.	Vision systems, traditional feeders or pattern picking, manually oriented	2 types of IRb SCARA and ASEA 6/2. Totally 4 IRb. Traditional sequence assembly
Mark II	Looped free-flow conveyor with pallets carrying exchangeable part specific fixtures.	Pallets on a looped free-flow conveyor.	Pattern picking from pallet or Orientation by a Vision system.	1 IRb ASEA 1000/2. Sub-assembly principle used.
Mark III	The part specific fixtures are carried in front of the IRb as it moves along a rail.	Manually on part trays placed on a fixed table or in traditional feeders.	Traditional feeders or part orientation by the use of a vision system.	A manual station for complex assemblies. Automatic mounting is performed by a 6 DOF ABB IRb. Sub-assembly principle is used to reduce gripper exchange time.
Sony Smart-cell	Free-flow conveyor with pallets carrying part specific fixtures between the FAA stations.	Pallets on a free-flow conveyor	A special designed system called APOS where parts are oriented onto part specific pallets by the use of vibration and air flow.	Mounting is performed by a SCARA IRb equipped with a special designed turret head with six tools.

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	<i>Process</i>			
<i>System</i>	Transfer	Transport	Feeding	Mounting
DIAC	Transfer is performed by a TTT handling system, i.e. a simple IRb on a rail that picks pallets from a storage shelf and presents them to the system.	Same system as the transfer system. Parts, tools and products are taken in and out of the system by an AGV.	Vision systems are used to orient parts outgoing from "right-side up"	Two IRb's that co-operate and partly share workspace. One 6 DOF ABB-IRb and one SCARA IRb is used. Advanced tools using transputers are used.
DRAS	Conveyor with pallets. Pallets have a standardized interface to fixtures	It seems like much of the transport is incorporated into the feeding process	It seems like mostly traditional feeding is used. The system modularity is more in focus than a general feeding solution.	The IRb module allows different types of IRbs. In literature SCARA IBM7547 and ADEPT One is used.
FAS	Looped free-flow conveyor with pallets. Assembly is not performed on the pallet. Coded pallets.	Transport is performed within traditional feeders. Magazines are filled manually	Traditional feeders and gravity magazines.	A SCARA type IRb, IBM7545 with exchangeable gripper-fingers.
HIFAS	Free-flow conveyor. It is not clear however if pallets are used	Transport is performed within traditional feeders. Magazines are filled manually	Traditional feeders and magazines	Different types of IRb's together with manual stations

4. FLEXIBLE AUTOMATIC ASSEMBLY SOLUTIONS

	<i>Process</i>			
<i>System</i>	Transfer	Transport	Feeding	Mounting
AMW	Conveyor with pallets. Pallets have a standardised interface to fixtures	Incorporated in the feeding process	A special designed feeder with three conveyors and a vision system	Mounting is performed by a SCARA IRb Adept 550.
MAX	Looped free-flow conveyor and an 6 DOF IRb hanging in a rail above the system. Modular fixtures	Not mentioned in literature	Not mentioned in literature. Probably traditional feeders.	The system is focusing on three joining techniques. Insertion, ultrasonic welding and clinching. The system consists of five IRbs.
DENSO	Conventional conveyor line with pallets carrying the work	Through general parts feeding units	General part feeding units	Free uncoupled mounting units consisting of IRbs placed on AGVs. The IRbs moves freely between assembly stations along the line

In Table 7 there is a short description of each systems contribution to the FAA system concepts. Note that this is the author's opinion. The system developers focus have varied and each system have made a contribution in some way to improve the abilities for FAA systems to meet the demands posed on them. The solutions of the key processes are in a way what make a system concept. As can be seen many of the systems have similar solutions to most of the key processes. A new approach to a key process is what makes a system unique. The key process solutions stipulate a lot of the flexibility in a system concept. It seems as if a physical independency between the key processes gives the system a higher degree of flexibility.

Table 7. Each systems contribution to the FAA system concept.

Mark I	<ul style="list-style-type: none"> - Moulded fixtures - Vision - Material transport to the system by AGV.
Mark II	<ul style="list-style-type: none"> - The sub-batch principle
Mark III	<ul style="list-style-type: none"> - Transfer is carried out by IRb on rail. - Integrated de-coupled manual assembly
Sony Smartcell	<ul style="list-style-type: none"> - Feeding system APOS - Modularity
DIAC	<ul style="list-style-type: none"> - Co-operation between IRb - Transfer by a TTT-handling system - “intelligent gripping” by the use of transputer technology.
DRAS	<ul style="list-style-type: none"> - Layered modularity approach
FAS	<ul style="list-style-type: none"> - Some modularity, expandable system - Some standardisation thoughts
HIFAS	<ul style="list-style-type: none"> - Nothing exceptionally new
AMW	<ul style="list-style-type: none"> - Specially designed general parts feeder - Modularity approach
MAX	<ul style="list-style-type: none"> - Joining techniques such as clinching, insertion and ultrasonic welding
DENSO	<ul style="list-style-type: none"> - Free uncoupled mounting process - Robust vision - Co-operating IRb’s

4.3.2 Flexibility summary

In section 3.2.2 on page 46 the flexibility concepts and terminology used in this thesis were explained. The flexibility was divided into static and dynamic flexibility i.e. off-line and on-line flexibility. In the previously described system concepts, one can see that the systems focus differently in this matter. The MARK systems

focus a lot on dynamic flexibility while, for instance, DRAS and SMART have a strong static flexibility focus. Of course, some dynamic flexibility is mandatory in an FAA system, but still the difference in focus is noticeable. Figure 30 shows symbolically the systems different focus.

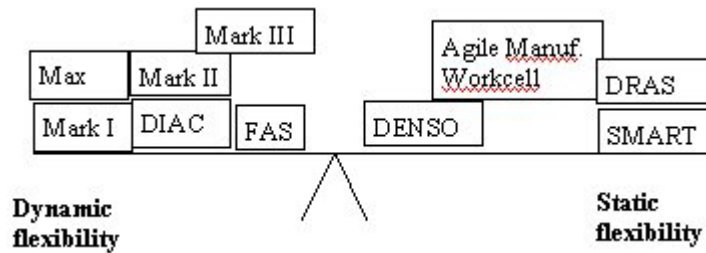


Figure 30. Symbolic picture of the flexibility focus for system in literature.

Both focus areas have their justification. The question remains as to what is the correct mix! In today's fast changing market and short product life cycles, the ability to quickly configure the system to unplanned new products and variants may be of great importance. The ability to quickly change the capacity limit up or down may also be important. All these are static flexibility issues. On the other hand, the extent to which a system should be able to handle change dynamically remains unclear. The variant explosion and demands on small batch assembly, to increase cash flow and throughput, makes fast change-over between configured variants/products necessary. However, one can see some trends towards a static flexibility focus. As a result, more and more modular assembly systems with high rebuild flexibility are appearing.

It would have been good if it had been possible to measure the flexibility for each of the described systems above against for instance a reference system. In this way one could easily validate the systems but since there is not a clear quantitative definition on what flexibility is, this cannot be done. Therefore only a qualitative judgement has been made while describing the systems, pin pointing out the difficulties and the way a certain solution is promising or not for a certain type of flexibility. In chapter 6 an attempt is made to propose a way to prioritise flexibility by evaluating the need for flexibility.

The difficulty for SME's in finding correct flexibility focus is a problem. The author believes that if the SME's were to find the correct focus for there situation, the implementation and use of FAA would be easier. In the next chapter a case study in a small company with the effort of implementing an FAA system is described. Hopefully the case study will give some answers on what flexibility is needed in a FAA system for small companies.

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5 CASE STUDY IN A SMALL COMPANY

In this chapter a case study is presented performed in a small company in Sweden. The case study was performed to learn about implementation of flexible automatic assembly in a small company.

Through contact with the academic world and visiting various conferences discussing FAA matters, some of the company's manufacturing engineers with direct contact to the shop floor believe that the use of FAA technology is the way to go. It is not, however, absolutely clear if the technology and its possibilities are understood. Top management needs to be convinced about the FAA technology's possibilities. So, one could say that the state at the outset of this case study is that the company knows about the technology and a few has a favourable attitude towards it. The case study is divided into three phases where the author's participation is large in the beginning and just observative during the last phase.

The three phases were the following:

- Pre-study
- Proposing an FAA system
- Observation of the company's implementation-work

As mentioned above, the middle management was more or less convinced that FAA is the way to go but they needed further evidence. The first step in the case study was to verify whether an FAA system was able to assemble some of the products. The manufacturing engineers needed more evidence to get the money needed to do the proper investments. Top management had to be convinced; so convincing top management was another purpose of the pre-study.

After the pre-study, a system proposal was presented. The system was then evaluated by the company's manufacturing engineers and a decision whether to continue or not was to be made.

In the last phase the company was carrying out the implementation completely on its own and the author was acting as an observer to document the problems and barriers for a successful implementation.

5.1 The Pre-Study

The pre-study consisted of two parts. First, the company as such was studied regarding the products, technology level etc. Secondly, the pre-study focused on the assembly of one of the companies products.

5.1.1 The company

The case study was performed in a small Swedish company producing water taps and other utilities for kitchens, laundry and bathrooms (e.g. mixer taps for wash basin's, bath mixer taps and showers). The company employs a total of 260 people divided into 70 white-collars and 190 blue-collars. Their turnover for 1996 was, 240 million SEK.

Their business strategy, in their own words, is " *to domestically and internationally provide a large variety of water taps with utilities that corresponds to our customers needs and expectation regarding quality and function*".

The company sells its products mainly to distributors and have little contact with the end-user. A small study made by the author has shown that the needs of the end-user do not affect much of the outcome of the products. It is the distributor, building firms, legislation or building services that set the main requirements for the product.

All parts of the products are developed and produced in-house with the exception of some commodity parts. According to the discussion in chapter 1 concerning different types of small companies this would be a company that is not just a supplier and has a good chance to take control over its future.

The product variant evolution

The business strategy presented above implies an increase of variants in the company and a study of the product catalogues shows a trend of increasing variety sees Figure 31. The decreasing number of variants between 1990 and 1993 could be explained by the depression in Swedish construction industry during that period. Since 1993 the variants are steadily increasing. This increase of variants indicates the need for more flexible manufacturing systems and assembly systems in particular.

Product variants over the years in the studied company

Variance due to change in color is not counted for

Product	1985-86	1988	1990	1993	1996-97	1998-99
Bath mixer taps	28	40	30	28	29	31
Mixer taps for shower	26	38	33	20	27	32
Basin mixer taps	24	33	30	18	23	27
Sink mixer taps	34	41	45	28	34	37
Electronically controlled mixer taps	0	0	0	0	0	7
Mixer taps for laundry's, trough basin's, restaurant's and flushes	25	34	28	22	22	21
Mixer taps for Hospitals and disabled's	15	21	19	13	17	17
Special mixer taps	15	16	16			
Total amount of variants	167	223	201	129	152	172
Changes in number of variants (%)		33,53%	- 9,87%	-35,82%	17,83%	13,16%

Figure 31. The changes in number of variants over the years at the studied company.

Products of this type could be considered mature and the competition is focused mainly on cost. Variants appear mostly due to styling or legislation. The technology development is mainly concentrated on better materials that facilitates and increase die-casting quality and decreases the use of toxic metals. Lately however, due to the higher demands on hygienic environments and better aids for disabled, the electronically controlled products has gained ground, see Figure 31.

The company's products, as mentioned before, are mainly produced in-house. The degree of refinement is high and some of the manufacturing processes involved are casting, machining, grinding, chromium plating, polishing and assembly. This means that the company has a lot of knowledge about manufacturing processes in various areas. They believe however that their "core competence" is in the casting process. Discussions with engineers and managers also confirm this.

The Assembly shop

The company's assembly shop consists of 60 employees and corresponds to about 43 full-time– 8 hours per day - workers. The average age of the personnel is 44. The budget was 14 million SEK, which consists to a large part of costs for the employees, 13.4 million.

Most of the products are assembled based on prognoses for the coming year. Every 3rd month the prognoses are adjusted by comparing to the actual manufactured volume during this period. These three-month prognoses are then distributed evenly over the period to achieve an even weekly manufacturing rate. At times with low demands the products are manufactured and stored on the shelf to manage periods with high demands. It has been hard to get some figures about the share of assembly to direct orders but its however not a big part. The change-over time between different products does not involve much change in the assembly area. Every assembly or a subassembly of a product has a more or less dedicated station and the change-over between different product means moving parts, components and personnel between the stations.

All assembly operations are manual with a few exceptions. Some of the O-ring assemblies and some of the really high volume components for the most common taps are assembled automatically with special purpose highly dedicated machines. The manual assembly is high paced monotonous work. To avoid/reduce the problems with repetitive strain injuries, the company applies job-rotation.

Status of the company

The conditions at the company will largely determine the ability to adopt new technologies. Questions that should be raised are: how do the company's present technology level, competence and education, organisation and product development affect the ability to implement new technology like FAA?. The possibility for a successful adoption of advanced manufacturing technologies depends largely on both the manufacturing system and the company as such. [Davis, 1986]. This implies that the FAA system approach must reflect the company's status.

The company's status is first described in these four areas :

- Technology level	- Competence
- Organisation	- Product-development

Technology level

As mentioned before, the products get a high degree of refinement as they are passing through the manufacturing process. The technology level is relative high in the early manufacturing steps. CNC-machines are used for milling, turning and drilling. Some special purpose lathes are used for high volume parts.

IRbs are a well-accepted technology at the company. Mainly anthropomorphic IRbs with six degree's of freedom are used. IRbs are used for automatically changing parts and tools in the CNC-machines and for various grinding and polishing operations.

5. CASE STUDY IN A SMALL COMPANY.

The investments in advanced manufacturing equipment vary along the product flow to final assembly. Every year large investments are made in the early manufacturing steps to improve quality and reducing cost. In the assembly shop however the investments are somewhat frugal. The investments are focused on replacing worn out special purpose machines or improve the fixtures and tooling for the manual assembly workforce.

Much of their products are manufactured in-house with the exception of a few commodity parts so all the manufacturing technologies are in fact available for manufacturing the whole product from raw material to finished products. This implies an organisation with a lot of competence in manufacturing processes.

Competence

The blue-collars level of formal technical education is rather low but it seems to be compensated by internal training of personnel. A large part of the workforce has been in the company for many years and has gained significant experience in manufacturing methods already in use at the company. However the lack of a higher formal education can sometimes limit the possibilities or the willing to approach new manufacturing methods and thereby, force them to rely heavily on vendors of manufacturing systems.

It is clear that the status of the work seems to be high at the early stages of the manufacturing where parts are “made” and low at the end where the product are simply assembled. A sign of this could be that low educated personnel work in the assembly shop.

On the engineering side few has a formal technical education above college-level and it seems that many of the engineers are recruited from the shop floor and trained internally. The little experience from higher education can explain some of the somewhat sceptical attitude against the academic world. This scepticism and the level of formal technical education can in many cases make the company sealed off from important new gains within the manufacturing system area, resulting in decrease of the company’s competitiveness in the long run.

Organisation

The organisation within the company is strictly hierarchical with a manufacturing unit with its engineers and workers, a marketing unit and a design unit. A clear sign of borders between these units is, that the manufacturing engineers and design engineers are separated by simply being placed in different houses in the company area.

Most of the manufacturing is functionally divided although some plans have been made for a more product-oriented organisation where the workforce is organised

along the product flow with responsibilities for planning, quality, education and training within the group and control of inventories. This is however not yet implemented.

The assembly shop has come a little further and has implemented team-based assembly with job-rotation and responsibility for quality and some planning. This is however not fully implemented due to for instance the problematic nature of workers with low self-confidence.

Product development

Although the design unit and the manufacturing unit are separated physically in different buildings there is not a pure “over-the-wall” mentality. The manufacturing unit is involved early in the concept phase of new products, discussing manufacturing methods and giving advice to the design engineers. The impression is however that it is more advises than rules forced to be obeyed so there is no guarantee that the designer will eventually care about the advises and guidelines given by the manufacturing unit. There is a clear sign of differences in seniority between the manufacturing engineers and design engineers where the design engineers seems to be the ones dictating much of the terms.

New products are initiated by the marketing unit in response to information on customer trends received from sales units around Europe. As mentioned earlier much of the customer demands comes from distributors and building firms. The major part of all new products is designed according to new styling trends. Therefore most of the internal parts remain the same through product generations while housing and knobs changes.

For internal parts the company has a product policy that says that all new parts and changes made to old parts or design changes to whole components must fit and work properly in older generations of the same type of mixer. The reason for this policy is that the company do not want to have separate manufacturing and inventories for spare parts. This policy has saved a lot of inventory costs over the years but it also has some big disadvantages on the behalf of design changes to improve for instance assemblability. Any major change to an existing design involves the risk of breaking the policy rule. The designers themselves do not know exactly from time to time how much a product design can be changed without breaking the policy rule.

The Company's motives for automation

In the outset of this case study a discussion was brought up concerning what the company believed to be the advantages of flexible automatic assembly or automa-

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tion in general. Their motives for automation in the assembly shop were the following in order of importance:

- Rationalisation
- Increase capacity and capacity flexibility
- Change the organisation and work into product flows
- Improvement of the work-environment
- Interesting work assignments

Rationalisation of the manufacturing in their opinion is the main reason for automation of the assembly shop. By automating many of the assembly tasks they hope to be able to cut down the assembly cost.

Today the company has problems with capacity and the shift in capacity need. The market is tightly connected to the construction industry, which have a shifting market. This means that from time to time the capacity is either too high or too low. By automation the company hope to be more capacity flexible. The automation would give them a chance to keep a stable and competent workforce and balance the capacity by controlling the pace on the automatic equipment.

Today the organisation is functional with the exception of product teams in the assembly shop. The automation would help the company to organise in product flows. The FAA systems configured for a product family and its variants would be a natural ingredient in product flow and the work force could be organised to support this system. Depending on if the system is doing the final assembly or a subassembly, the assembly teams work assignments will change accordingly. In the case of the system doing the final assembly, the team might support the system with subassemblies and filling feeders and pallets and doing the final adjustments and quality check before packaging. In the case of the system doing the subassembly the work force might order from the system the number of subassemblies needed for the final assembly. In either way the system would be a natural part of a product flow.

Over the years the company has had problems with injured personnel due to monotonous work assignments and a high pace. To avoid this the company has utilised job-rotation, advanced fixturing and more or less automated tools and equipment to support the work. This have improved the situation but far from solved the problem. By automating a longer sequence of operations the company hope to be able to isolate hazardous operations from the workforce.

As mentioned earlier, the status of assembly work seems to be low compared to other work in the company. The reason for the lack of young educated personnel in the assembly area is that it is not considered an interesting work. This could in

turn be due to low technology content. The turn-over of personnel in the assembly shop has been decreasing in recent years but it is believed to be as a result of the depression in Swedish industry and will probably increase again. The company fear, that the youngsters in the assembly shop will be moving on to more interesting work or continue their education and in either way be lost for the company. The turn-over of personnel will be a costly matter with continuous education of newly hired personnel. That is, of course, if they can get hold of any. An automation of the assembly area will increase the technology level and hopefully attract young educated personnel that will find the work interesting and challenging and help the company to continue develop these skills.

The reasons for automated assembly discussed above are well known facts within the research community. Some other positive outcomes of automation that were not mentioned by the company are the possibility to attain a more consistent product quality or the possibility to lower their levels of inventory.

5.1.2 Assembly of a company product

A part of the pre-study were performed at the laboratory at Högskolan Dalarna, where an assembly cell was built to answer questions such as:

- Is it possible to assemble the products with FAA technology?
- What would the assembly capacity be?
- What assembly principles should be used?
- How should the system components be designed?
- What changes has to be done to the existing product?

The manufacturing engineers needed more evidence to be fully convinced of the FAA system abilities and the pre-study tried to show that it is possible to assemble the product with an IRb.

The assembly capacity had to be investigated and the operation times were documented during testing in the laboratory. The operation times were later used to estimate the possible capacity when the proposed system solution was evaluated.

The laboratory testing was used to evaluate the proposed assembly principles and give suggestions on how to design grippers and fixtures.

As in the majority of cases, it is not possible to assemble a product without adjustments to the product design. One of the purposes with the pre-study was to identify weaknesses in the product design, regarding automatic assembly, and to propose design changes.

Product and assembly structure

Already in the beginning of the pre-study it was assumed that the company had little resources to set aside for the project, so a minimum of expenses was important. This assumption became more and more valid as the study went along. To keep the costs down the product chosen had to support assembly in one direction. This would make it possible to use simple IRbs like a SCARA. The product should be in several variants to utilise the flexibility in FAA systems as discussed in previous sections.

The product chosen comes in three variants with a total yearly volume of approximately 100 000 units., Figure 32.



Figure 32. The three variants of the product.

Depending on variant the number of parts varied between 8-10. Most of the parts were the same for all the variants [Johansson, 1997]. It is important to reduce the number of parts to facilitate automatic assembly. It was therefore interesting to see that parts from suppliers are the same in all of the variants but parts designed in-house vary between the variants. An explanation could be that the parts from suppliers are standardised commodity parts. One could say that it is the company that creates sometimes unnecessary variants, probably unaware of its consequence for automatic assembly. However, the parts were almost identical in all variants and would entail similar problems during assembly so the testing therefore focused on the variant with the largest number of parts (10 parts).

The manual assembly structure was analysed, Figure 33. It was considered important to reduce the number of subassemblies to simplify the transfer process in the FAA system.

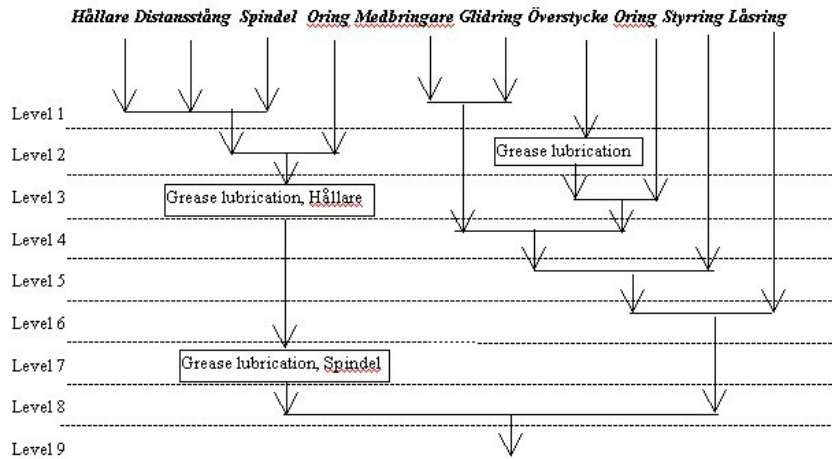


Figure 33. Assembly structure for the manual assembly.

The assembly structure showed two main subassemblies that are assembled in the final assembly. In order to simplify the fixturing, transfer, feeding and transportation, an effort was made to change the assembly structure. The goal was to have a pure base-part assembly. Most of the assembly operations were made top-down which is well suited for a SCARA-IRb. A study of the product and the assembly structure showed that the subassembly *Hållare*+ *Distansstång*+ *Spindel* could serve as a base part. After some design changes the assembly structure was changed to what is shown in Figure 34. With some exceptions it is a pure base-part assembly. Due to this change of structure, the parts can be transported in one sequence to the FAA system and the finished product can be assembled in one sequence without the need of buffers for subassemblies. This was an important factor when building the testing cell described in next section.

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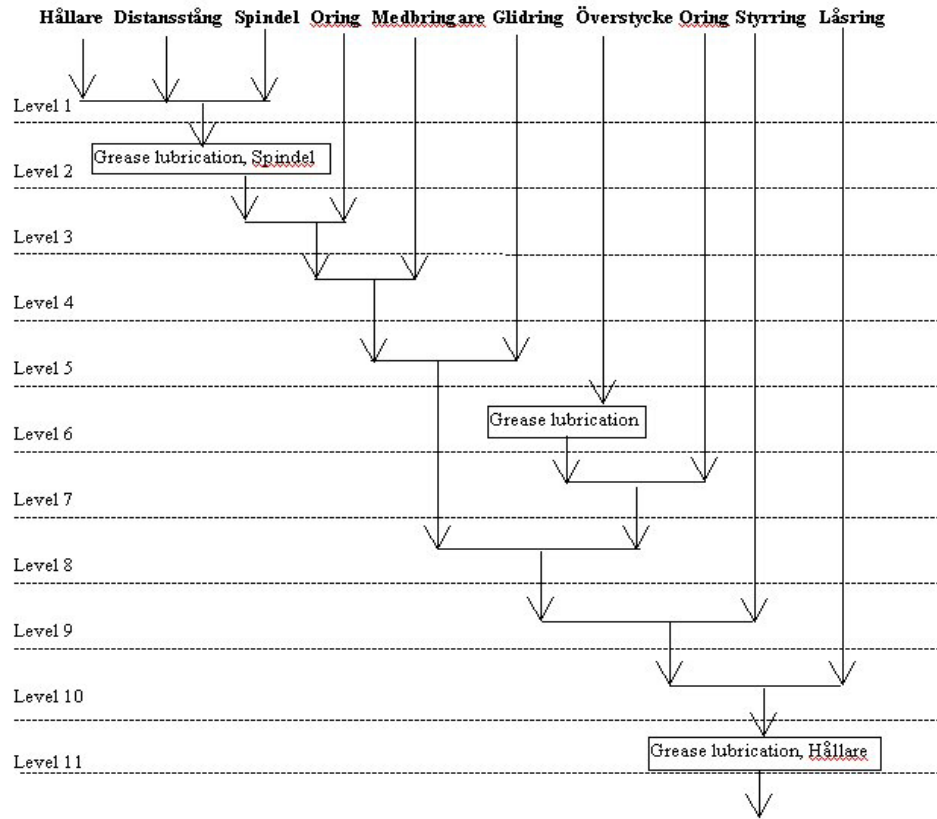


Figure 34. Re-designed assembly structure for ease of automatic assembly.

The laboratory test cell

In order to propose an FAA system for the product the author has built a test cell in the laboratory at Högskolan Dalarna, Sweden [Johansson, 1997]. The purpose of the test cell was to evaluate assembly principles, fixturing and point out necessary design changes for the product. During testing, operation times were documented for later use when calculating possible capacity. Another important purpose was to visualise the assembly problems that may occur. By physically showing the assembly problems it was much easier to gain understanding for the product design changes needed.

The test cell consisted of a SCARA-IRb and an indexed turn-table. Programming of the IRb and equipment was simplified by using a PC-based controller system

with the programming language AML/2¹⁴. The control system supported some simultaneous running programs thus eliminating the need for a PLC-controller. Parts were fed to the IRb on pallets placed on the turn-table. The filling of pallets proved later to need a too large amount of manual work. However for the testing this was a low cost solution that would do. The figure below shows the test cell, Figure 35.

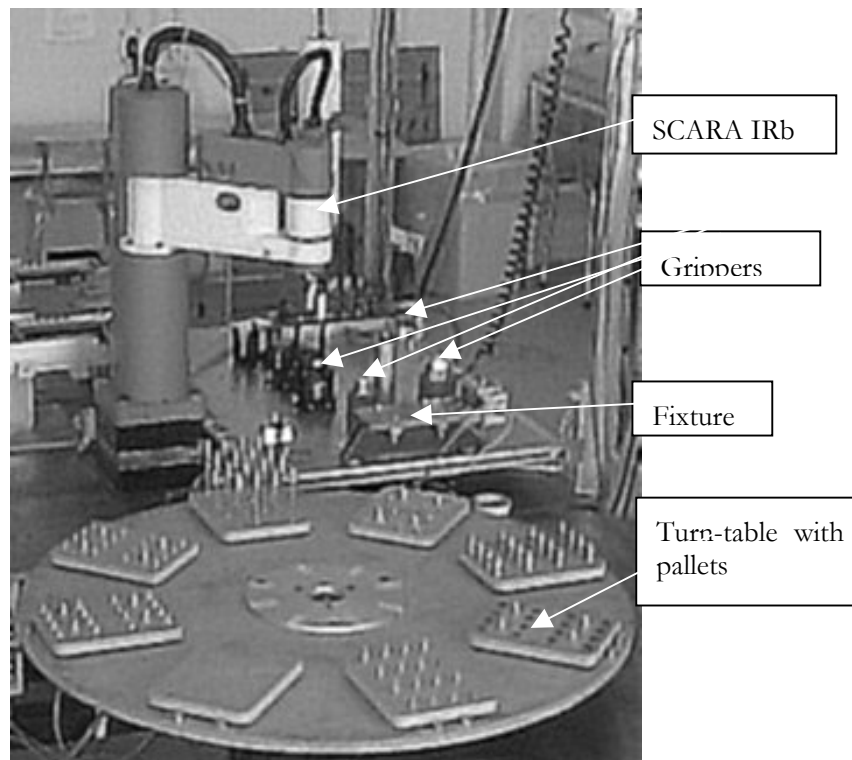


Figure 35. A picture of the test cell at Högskolan Dalarna, Sweden.

¹⁴ A Manufacturing Language, AML/2. A programming language for industrial automation introduced by IBM.

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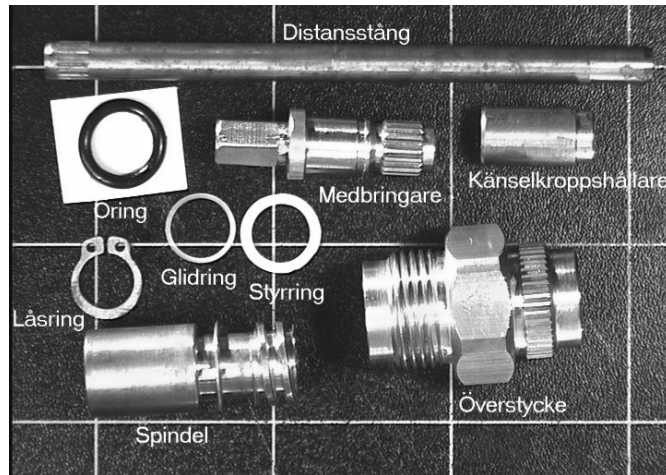


Figure 36. The parts that were to be assembled in the case study.

Testing of grippers

The gripping and mounting of each part was tested and grippers were designed. Figure 36 shows the parts tested with the exception of the *Oring* for *Överstykke*. Table 8 shows the results from testing.

Table 8. Results from the testing of grippers

Part	Operation	Gripping method
Spindel + Hållare + Stång	Placed in fixture	Parallel gripper
Oring for Spindel	Mounted on <i>Spindel</i>	Special purpose gripper supplied by vendor
Medbringare	Mounted on <i>Spindel</i>	Special purpose gripper designed by the company
Glidring	Mounted on <i>Medbringare</i>	Vacuum gripper designed by the company
Överstykke	Mounted on <i>Spindel</i> .. The oring for <i>Överstykke</i> are first mounted on <i>Överstykke</i> by a special tool from below i.e. bottom-up	Parallel gripper + a special purpose tool for orings placed in the cell for mounting from below. Special purpose tool supplied by vendor

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

Överstykke	Screwing onto <i>Spindel</i>	Special screwing device supplied by vendor
Styrning	Mounted on <i>Överstykke</i>	Vacuum gripper designed by the company
Låsring	Mounted on <i>Medbringare</i>	Vacuum gripper designed by the company

Design and testing of grippers were not a problem since the company have specialists in tooling. The grippers were designed and tested within a few weeks. Some of the assembly operations were considered easy and only a simple temporary gripper was made to be able to do the whole assembly. In the real manufacturing situation standardised grippers from vendors will be used for the easy assemblies. The grippers designed in-house were not optimised. In some cases a failing gripper-principle gave the idea to another.

Product design changes

During the testing some design changes had to be done. The designers were not used to this kind of changes proposed by the group responsible for assembly. Most of the proposed changes normally come from the machining shop. With the test cell performance as evidence, most of the design changes were not hard to motivate. The designers however, were very eager not to increase the costs in the machining shop and therefore did not like the idea of integrating parts to reduce the amount of parts in assembly. Design changes were considered to increase cost in the machining shop without any thoughts about how the changes could mean a major decrease in assembly costs. As a consequence the design changes were part oriented only (no part-integration to reduce number of parts) and changes were made to ease gripping mounting and feeding. The most common DFA-rule used was to make the parts symmetric.

Part	Change	Comment
Hållare	Made symmetric	<ul style="list-style-type: none"> - Removing part features no longer used. - Easier to feed

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Stång	Made symmetric	<ul style="list-style-type: none"> - Easier to feed - Designer not sure why the part is made asymmetrical in the first place.
Medbringare	<ul style="list-style-type: none"> - Chamfer angle - Thickness of flange 	<ul style="list-style-type: none"> - Removes the need for a special purpose tool
Glidring	<ul style="list-style-type: none"> - Remove 	<ul style="list-style-type: none"> - The designers do not want to remove this part because it is not clear what will happen to the product functionality.

Operation time evaluation

When design changes had been made, the testing cell was used to document operation times for each operation. The operation times can be seen as maximum operation times and can be used to estimate a possible capacity level for the system using these assembly principles. Operation times can be improved by for instance optimising the IRb paths, improving the cell design, improving the grippers and try to increase the IRb speed. The IRb's path speed was however not easy to adjust as it had a large impact of the assembly reliability.

All operation-times were not measured due to limited time and resources. The pressing operation of *Stång*, *Spindel* and *Hållare* was not tested as it consisted of simple pick and place operations. These operation times were estimated equal to similar tested operations. A total of 24 operation times were tested or estimated. The table below shows the results where similar operations are grouped together.

Table 9. Operation times measured in test cell

Operation	Measured Time [mean value / range] [s]	Time used in capacity calculation [s]
Changing of grippers	8.0 / 7.8-8.4	8
Pick and place operations with parallel gripper	6.8 / 6.7-7.2	7
Assembly of <i>Medbringare</i>	10 +/- 0.5 *	10
Assembly using Oring-gripper or Vacuum-gripper	6.9 / 6.7-7.3	7

*) Estimated time outgoing from the experience gained in measuring the other operations.

The operation-time for the assembly of *Medbringare* could only be estimated. The assembly principle used in the test-cell was not applicable. The assembly was performed by letting the IRb “feel” when the hexagonal patterns matched, using a force sensor. This was interesting in an academic point of view but was not suited in a real production situation as the operation could continue for more than 30 sec.

Discussion

Grippers designed to handle more than one type of part is a risk for the systems reliability. This has been shown during the testing. By compromising in this way the gripper will not be suited for either part, and the risk for failure increases. One should instead use the sub-batch principle, [Arnström & Gröndahl, 1988b], and a specific gripper for each operation as done for instance in the MARK III project. [Langbeck, 1998]. The problems in the test cell can be seen as additional evidence to this fact.

Pallets versus feeders? In most cases the pallets show a higher degree of flexibility and lower cost than for instance dedicated feeders. The positioning accuracy of the pallets was however a problem from time to time. If positioning a pallet consisting of for instance 16 parts placed in a pattern on the pallet, one are actually positioning and determining the state of 16 parts. That is, if the pallet is slightly out of position perhaps only 12 of 16 could be picked correctly.

The IRb’s path speed impact on reliability was clearly shown in the test cell. By decreasing the path speed slightly the reliability increased significantly. This could be a good choice in situations with reduced personnel on a night shift. Instead of chasing parts of a second a reliable system would then be more important. With the results from the test cell in mind a system solution was proposed. This is discussed in the next section.

5.2 Proposing an FAA system

This section describes the proposed system solution. The test results from the test-cell had convinced the manufacturing engineers at the company and they wanted a system proposal to evaluate and have as a base for further discussions with management.

5.2.1 Requirements

The company insisted, despite the increased system flexibility, to have a pay-off time of 2 years. The limitation of 2 years reflects the company’s uncertainty concerning the FAA technology. It also shows that they have not understood the

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potential in an FAA system. The 2-year limit originates from their earlier experience from investments made in the dedicated equipment. In their point of view an FAA system seems to be a more complex dedicated system.

A policy within the company that originates from work-environment and cost reasons says that manufacturing should be performed during day shifts. There is no other production performed in evening- and night shifts so they don't want to leave the assembly personnel on their own on these shifts.

With these two limitations above the project could easily have been called off because it is not possible to economically justify an FAA system under these circumstances. The project proceeded though, in the hope that they would reconsider their requirements when they had learned more about FAA. At the same time as they have this cautious attitude they realise that they have to learn new manufacturing methods.

The final requirements for the FAA system were therefore determined with these two limitations not considered fixed. To support the situation at the company the author added some additional requirements. The final requirements were the following :

- A total volume of ~100 000 units/ year (10 000 +10 000 + 80 000)
- A pay-off time of 2 years (not fixed)
- 1-shift (not fixed)
- Possible to stepwise build the system in a pace determined by the company's capacity need, increased competence and ability to invest.
- The system should also support the possibility to introduce new products into the system without a to large impact on the existing manufacturing.

The incremental steps in which the company can build the system is largely determined by the fact that the system has to be able to do something productive in all steps and the steps are therefore rather large.

The test cell has shown that one can assume that the FAM cell can be unattended for approximately 2 h at a time before filling feeders. If this is the case then the 1-shift can be described as in Figure 37. The total possible assembly time for the system would then be 11h, which would lead to possible yearly time of 2475h.

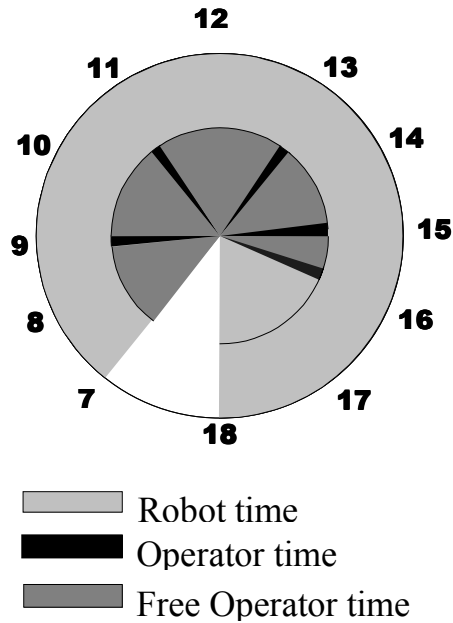


Figure 37, Definition of 1-shift.

5.2.2 Capacity estimation

With the use of the operation times from the test cell the system capacity was estimated. A single stand-alone cell would need approximately 2525 hours to assemble the 80 000 units of variant A and approximately 476 hours to assemble the 20 000 units of variant B and C when using a sub-batch of 20 (sub-batch principle), Table 10. Variant B and C were very similar and are treated as the same assembly. According to the 1-shift definition, in Figure 37, this will not work due to lack of capacity.

Table 10. Volumes in a single FAA-cell

Product variant	Assembly time needed [h]	Volume [units]
A	2525	80 000
B+C	476	20 000
Total	3001	100 000

To increase capacity the choice would be either to assemble in parallel with two identical cells or in serial dividing equipment between cells. In the first case a re-

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dundancy will appear but with high additional costs and a more complex material flow in the shop. In the second case the cost for equipment will be only slightly higher than in the single cell case but with a higher risk for stops and balancing problems. Due to the company's limited resources the cost was of high priority so the approach with serial assembly was chosen.

After dividing the work between the two cells a recalculation of assembly times needed for the different variants was done. Table 11 shows that the new system approach needs approximately 1503 hours to assemble 80 000 units of variant A and approximately 337 hours to assemble 20 000 units of variant B+C. Total assembly time needed is 1840 hours. All capacity estimation has assumed 100% availability, which is rarely the case, but 1840 hours gives a margin to the 2475 hours available (Figure 37) that well compensate this. In the next section is the proposed system layout described.

Table 11, Volumes with two FAA cells in serial

Product variant	Assembly time needed [h]	Volume [units]
A	1503	80 000
B+C	337	20 000
Total	1840	100 000

5.2.3 Layout

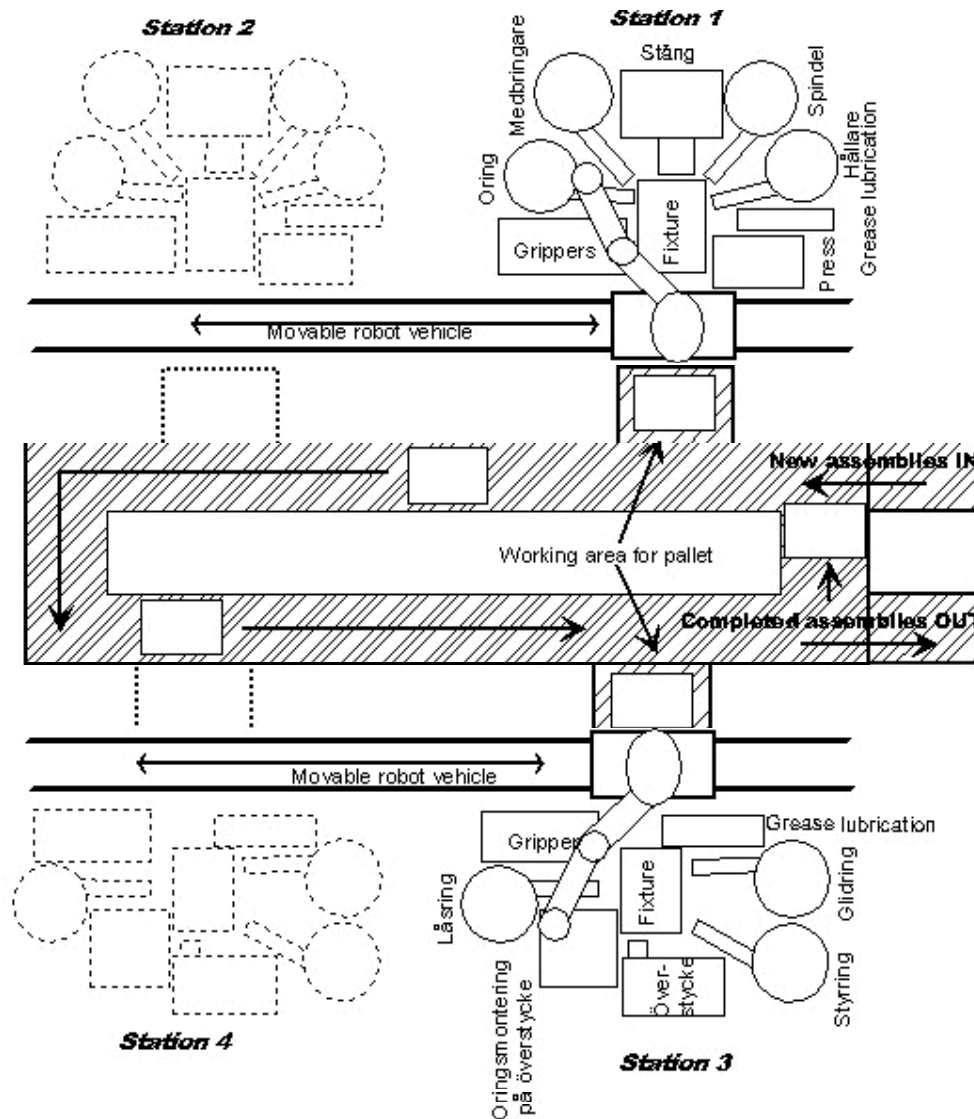


Figure 38. The proposed system layout with two FAA cells in serial, connected with a pallet conveyor.

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Figure 38 shows the proposed system layout with two FAA cells working in serial linked with a conveyor. This system layout is supposed to support the requirement of stepwise building and introduction of new products as discussed in a previous section. The company can start small and assemble only part of the product while learning more about IRBs and their assembly ability. While building, the IRb should be placed on a short piece of the track to be able to continue building without any changes to the already built cell. One can start with “station 1” and continue with “station 2” when time; competence and cost situation allows it. “Station 3 and 4” can represent equipment for another product later on or a subassembly of the present product.

Key processes

The transfer is performed by the use of conveyors as in many of the described systems in section 4. The conveyor is serving as a buffer and interface to the surrounding activities in the assembly shop. The base-parts (a sub-batch) are placed on pallets. The fixture is fixed in the FAA station and the IRb unloads the pallet and loads the fixture before the assembly can continue.

Transport is done as a part of the feeding process. Feeding is done by the use of vibratory bowl feeders and gravity magazines. The company has experience in this type of feeding solutions. A pressing tool is integrated in the system.

A SCARA IRb performs the mounting. Exchangeable grippers are used to increase geometrical and technical flexibility. The gripper exchange method is similar to the one used in the FAS-system [Holmstedt, 1989].

Dynamic flexibility

The technical and geometrical flexibility is low. The system is very focused on the three variants discussed earlier, although the exchangeable grippers contribute to technical and geometrical flexibility.

Routing flexibility in the system is focused on batches and orders. It should be able to change between orders and batches. The ability to change sequence of operations are not good.

Change-over flexibility within a station is focused on the three variants, however if more stations are put along the track it is easy to move the IRb between the stations and assemble different products. Since there are no sharing of parts and tools between stations the change-over flexibility is poor due to a high cost/flexibility ratio.

Volume flexibility can be achieved by reducing the assembly speed by changing between products and variants more often (increased set-up time) allowing the

IRb to travel between configured stations. The volumes will decrease due to less effective system use.

Static Flexibility

To increase the product-, variant- and change-over flexibility the IRb is placed on a movable vehicle similar to the Mark III system [Langbeck, 1998]. As new products or variants are introduced, equipment can be placed in a separate station along the track or, if possible, to an existing station. However, due to the poor material and tool sharing possibilities between stations the flexibility may be costly.

The track is mainly used to increase the IRbs workspace. Capacity is directly connected to the mounting process. In order to increase capacity the number of IRbs has to be increased. The system concept makes it possible to increase or decrease the capacity by simply add or remove IRbs. In times with low capacity need one IRb handles several stations. In this way there are well-defined “least common divisors” in the system. The capacity flexibility is therefore rather high.

In order facilitate the installation and implementation of FAA at the company the flexibility focus has been more on static flexibility than dynamic flexibility. To have a high level of dynamic flexibility means often higher technical contents in the system which means that the skill of the installers and implementers must be high. It was assumed that this was not the case at the company and the focus is on static flexibility.

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Table 12 Some of the Pros. and Cons. of the proposed system

Pros	Cons
Stepwise upgradeable or rebuild.	All the products may not be suitable for transportation on a pallet.
Development of new stations along the track during on going assembly.	Feeding resources cannot be shared between stations if different products need the same part.
Some redundancy can be achieved as another IRb can take-over a limited set of operations.	The station themselves are fixed and incorporate no automatic change-over abilities
One IRb can co-operate with itself by doing some assemblies in one station and then move to the next and call the pallets back in.	
A product can be assembled in parallel or serial depending on the station configurations	
Different products can be assembled in the system simultaneously.	

5.2.4 Facts of Economy

The company limit of 2-years pay-off makes the justification of this kind of system hard; the 1-shift limit makes it impossible. A cost calculation including hardware, engineering, education and installation was summed up to approximately 2.5 million SEK. The system was estimated to give a yearly return of investments of 210 000 SEK. Savings taken into account was pure cost reduction by reduced wages. Savings generated due to a more consistent product quality, reduced costs for repetitive strain injuries and so on were not possible to estimate and the company would therefore not accept these arguments. A pure pay-off calculation without any concern about inflation and interest would show a more than 10 years pay-off time. Perhaps the system costs are a bit too high. The system costs have been estimated by using brochures and sales contacts but in the eager to be honest and not be miss-leading, costs that have been uncertain have been set rather high. This kind of system needs to be run in several shifts, which means more product variants in order to be justified.

Despite the 10-year pay-off time the company was not immediately discouraged. Instead they decided to continue the work on their own. The test-cell had served

its purpose and shown the manufacturing engineers that the assembly was possible and given them ideas and concepts to explore further. Perhaps the technical interest overcame the discouraging facts of economy. They started however soon after this pre-study to investigate if it was possible to start smaller with a sub assembly of the studied product.

The project turned into another phase that could be stated to be an implementation phase. The pre-study had served as a decision support and forming of positive attitudes, at least for the manufacturing engineers. A decision to try to implement FAA, beginning in a small scale, was taken. A small FAA cell for assembling a subassembly of the studied product was to be built initially. This small step taken was probably due to the lack of company knowledge within this area and the cell will serve partly as an education attempt. The next section describes the work with this cell, the author from now on only acting as an observer.

5.3 The observation phase

The decision to implement FAA had probably not been made without the previous work with the test cell. Despite the discouraging economy of the proposed system, the company has found some advantages with the FAA technology. In a sense one can see the previous described work as a presumption for this observation phase.

5.3.1 Observations

Initial initiatives towards an FAA cell started with the effort of finding suitable hardware. The company was at this point working within “station 1” in proposed system, see Figure 38 on page 106, at least that was the impression the author had as an observer.

Acquiring and integration of system components

Suppliers of the equipment were more or less treating the system they are delivering as a turn-key system meeting the specifications of the end user, i.e. the studied company. As there is no true system vendor for the whole assembly system, just the different systems that it consists of, there is no true outside support for the integration of the different systems and the company has to rely on their in-house competence.

Programming of the system was and still is a problem in the company. Despite some efforts to learn the basics of programming, it is a major barrier for future development of the system.

The company’s previous use of advanced technology in the form of machining-centres, robotics and the competence and resources which comes along with that

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use, have been proven an important factor when trying to build the cell and acquiring equipment from vendors. The tooling expertise had no problems making the grippers needed and since they have some dedicated assembly machines in the assembly shop they also have experience in feeders. No problems, means that there was no lack of competence in this area.

Product changes

The company discovered the product-process dependency in the form of low system reliability and costly system changes. This has resulted in higher quality demands on the company's suppliers and in-house manufacturing units.

As mentioned earlier, some design changes had to be made on specific parts. Despite this, designers have trouble to accept that they have to change the way they are designing parts and components. They are putting the complete responsibility for the FAA systems functionality and reliability on the manufacturing engineers. Some efforts has been made by other researchers to involve them in studies about DFA but the designers have so far not been interested. Hopefully the work with the FAA system will convince them of the advantages a DFA approach.

Resources

In the studied company there is no strategy for the implementation of FAA. The ongoing activities seemed to be explorative based on trial-and-error. The manufacturing managers had seen some advantages with FAA and were trying to come-up with a system that could be shown to the top-management in order to get resources for further implementation.

The time in this project was crucial in more than a cost aspect as the results had come quickly before the managers started to have doubts. The doubts increased quickly as time went by and no results were presented. But still having this demands on quick results the project seemed to have a low priority as no personnel resources were reorganised to support a quick installation of the system. Since there was no formal reorganisation to support the installation efforts, the work was treated as a local assembly shop problem by the rest of the company personnel. This made it even harder to get in-house priority for e.g. producing grippers and fixtures. Most of personnel involved had to do the work on their "spare time" (i.e. when the daily routines were done or allowed it). The key persons in the organisation possessed most of the competences and they had very hard to manage this "spare time" work. An example of this was the manufacturing manager responsible for the technical issues in manufacturing. He was also responsible for the installation of the FAA cell and with no resources at hand in the form of competent personnel he had to do a lot of the work himself on "spare time".

Another sign of the missing strategy can be seen in the way they have built the system. The system was treated more or less like a dedicated system. The IRb was therefore blocked from other possible assemblies in the future by being surrounded with more or less dedicated equipment leaving no openings for, for example a movable IRb as was shown in the system proposal. The company was so eager to get this system working that they didn't have time to look ahead and plan for future products and future use of the flexible equipment. There is a risk that the company end up with a system that only will be useful for old established products and not be capable of incorporate new products.

Competence

The company lacks experience and educated people in the area of programming. They have therefore been forced to hire consultants to do most of the programming of the FAA system. Their own need for education has however not been ignored. A key person was participating during programming trying to learn the basics. This key person had then the responsibility to preserve this knowledge within the company and to educate and train the personnel concerned. The company want to manage on their own and avoid a dependency relationship with a vendor. However, programming is not something you learn quickly if you are an inexperienced programmer, this was shown in this case study. If the programming is an obstacle then the development of the system will suffer, as the possibilities for the system are not fully understood.

As the company was building the system more or less by themselves by putting different sub-systems together from various vendors, they were "learning by doing". The true understanding of the potential of a well planned and company supported FAA system was very limited as they had a very narrow focus on what-is rather than what-to-come.

The time aspect was obvious in another way in the project. Trial and error takes time. During the project a decision was made to phase out the focused product so the system was almost out of date when it was up and running

Education of design personnel to support the FAA system seems very distant for the moment. Although some efforts has been made on a part level to raise the reliability of the system. The true potential however, where they are taking the FAA system into account on every new design or design change seems for moment to be far away.

Personnel

They try to have a long-term plan for the human resources. They have up to today, only at a few occasions been forced to lay-off personnel due to rationalisa-

tion. Rationalisations have so far been handled by moving personnel to other areas in manufacturing and not hiring new workers when personnel are retiring. This is a policy in the company that rules. By doing the rationalisation stepwise they can handle the human resources for the moment.

5.4 concluding discussion

There are three main factors that can be pointed out as problem areas when trying to implement FAA in small companies:

- Learning the technology
- Product design
- Strategy for implementation

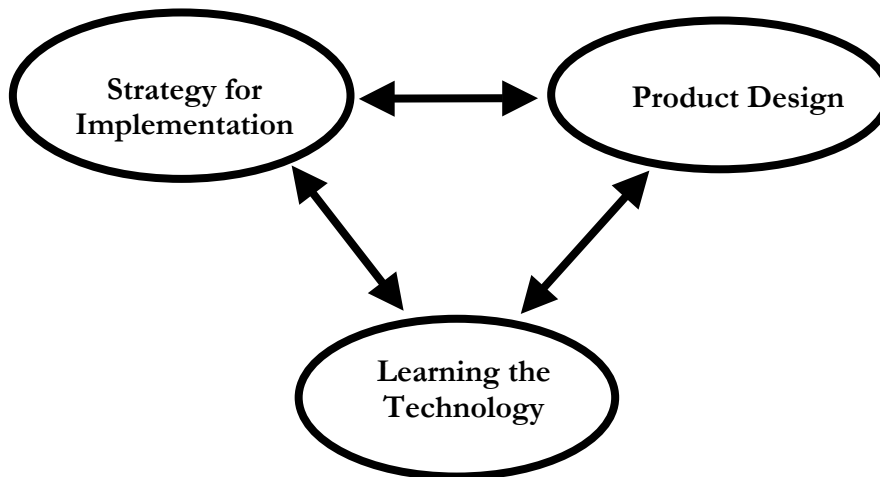


Figure 39 Interrelations between the three barriers for implementation.

The three factors are tightly connected. If the implementing company does not fully understand the technology, they cannot set up a good strategy for implementation. With no strategy, there is no driving force to adjust the products to the technology. With no or little knowledge of the technology the products impact on the system is not understood and design changes are hard to motivate. Not knowing what changes to do to adjust the products to the technology is another consequence of not understanding the technology.

5.4.1 Product design

If the small company has little experience in automatic assembly the manufacturing unit has not gained enough knowledge to be able to guide their designers to design products for automatic assembly. It seems hard to motivate designers to

design for automatic assembly as long as they don't have a system implemented. It seems that most companies initially believe that they can install an FAA system without any changes to the product assembled and it is therefore hard to convince a company of the advantages of DFA without an automatic assembly system at hand.

Due to a short sighted and functional oriented view that does not take into account the costs along the whole product flow, companies sometimes do not perform changes defending the decision with increased costs in part manufacturing.

5.4.2 Learning the technology

It takes time to learn and fully utilise the potential of an FAA system. Since a successful use of FAA is tightly connected with product strategy it is hard, if not impossible, to isolate an implementation effort to hardware solutions.

The small company need to learn the technology stepwise but the economical issues sets limits for the size of the steps. A system must be useful in all steps and bring a return of the investment. The system complexity and the economical issues makes the learning steps larger than the small company can handle. There is a risk that the system is already out of date when it is up and running, due to a too long learning period.

Due to the lack of FAA knowledge, changes that have to be done when upgrading the system must be planned for when designing the system. Otherwise no changes will be performed and the development of the system will be frozen due to the risk of harming the ongoing assembly process. In other words, due to lack of competence, nobody dares to change anything when the system is up and running due to the risk of jeopardising the stability and reliability of the system.

5.4.3 Implementation strategy and justification of the system

It seems like the desire to implement FAA often begins in the manufacturing area and therefore there is a lack of strategy for its accomplishment, there is no true top-management support. The efforts tend to be a local phenomenon in the assembly shop.

The economical justification of an FAA system has shown to be a problem. But this is also partly due to the lack of strategy. Instead of seeing the FAA system as an opportunity to make money they are focusing the FAA efforts on cutting costs. An explanation to the cutting cost focus could be that if one does not have a strategy when implementing FAA in the company one does not know much about the future development of the system and one does not see the long-term advantages. Furthermore, if one does not have this long-term view of the system

5. CASE STUDY IN A SMALL COMPANY.

one has to evaluate the system and defend/justify its existents with the actual products currently produced in the relation to the close future you know of. This means pay-off calculation with short- pay-off times reflecting the uncertainty due to the lack of an implementing strategy. Some of this thoughts are mentioned by for instance [Yxkull, 1994]

The next chapter will discuss and point out the direction for changes in order to develop FAA systems outgoing from SME perspectives as proposed in the hypothesis in the beginning of this thesis.

6 REQUIREMENTS AND THE PROPOSED NEW APPROACH

This chapter contains discussions and proposals on ways to solve the problems found during the empirical and theoretical studies. A brief presentation of implementation of technology in literature is presented. Experience from the literature study is also used. The new definition of flexibility is analysed and a new approach is described.

The basic research questions were detailed in section 1.7, “Research questions of this thesis”. One of the questions was: *What are the prerequisites/requirements concerning flexibility and structure posed on FAA systems in order to facilitate the use and implementation of such systems in small companies?*

Now, based on the findings in the studies, the next step is to verify whether the data and results collected in the case study, may be exploited for the design of FAA solutions that ease the following:

- Learning of the technology.
- Integration/accounting of product design issues such as, for instance, product plans and part design.
- Implementation despite an initially “weak and uncertain” strategy.

This chapter is structured as follows:

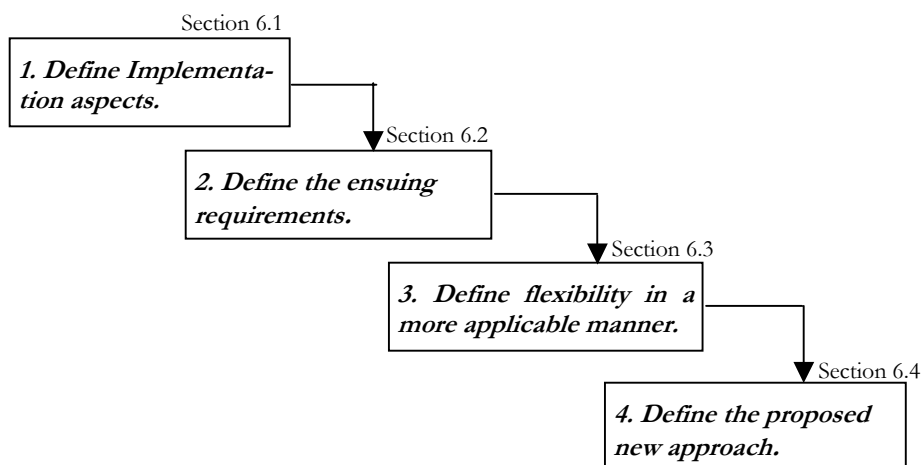


Figure 40. The structure, objectives and line of logic in chapter 6.

6.1 Implementation of technology

As mentioned earlier the words *implementation* and *installation* have been used according to the following definition: *Implementation* of FAA means to install a system and fully understand the FAA technology and its effects on all areas of the company. In other words, after an implementation one have the “FAA mindset” in the company. To *install* an FAA system means to physically build an FAA system on the shop floor.

Studies have been conducted on the adoption process of new innovations into large companies [Davis, 1986]. Although FAA systems are not considered innovations in general they may be considered to be so for small companies that recently discovered the technology and try to implement it with the somewhat limited resources they have. *Onori et al.* pin points the ever-present constraints afflicting SMEs [Onori et al., 2000]:

- Low investments possibilities.
- Low competence levels.

6.1.1 Implementation aspects

John E. Ettlie conducted a study in the USA in the mid 80’s, where he studied the factors important for a successful implementation of new technology [Ettlie, 1986]. *Ettlie* observed that firms that tried to implement advanced manufacturing technologies experienced a considerable variance in success. *Ettlie* derived a general hypothesis that suggests that a successful implementation strategy is matched with the characteristics of the implemented technology. Some of the factors found in the study can also be important when developing and structuring hardware solutions for easy implementation of FAA in small companies [Ettlie, 1986]:

- Supplier-user relationship
- Product – process dependency
- User strategy
- Incremental implementation strategy
- General management support
- Participation
- Justification
- Size, structure and organisational culture of the company
- Training

6. REQUIREMENTS AND THE PROPOSED NEW APPROACH

This list will be used to further discuss the observations made to date by the author and others.

Supplier-user relationship was denoted a very important factor. Teams with key people, from both the supplier of the equipment and the user, working tightly together to reach the goal. The systems do not install themselves. They are complex enough and tailored enough such that there are no turnkey installations [Ettlie, 1986]. In a complex system like FAA-systems very often there are several suppliers of system components, each which have its own performance target, unaware of the complete set of demands posed on the component by the whole system. This results in a system for which the performance tend to be slightly unpredictable, and needs a lot of maintenance, from the vendor responsible for the whole system [Mårtensson, 1995b]. There exist no approaches in which a vendor can come up with the support that can compensate for the fact that the user does not fully understand the system. The user has to assimilate the system. An example of this is for instance the implementation of the FAA-system Mark IIF at Atlas Copco where the company had to rely on the vendor for programming [Mårtensson, 1995].

Product process dependency: How well a company succeeds in the implementation of a new technology depends largely on how well they understand this dependency. The basic questions to be asked regard:

- Whether it is the right technology for my manufacturing system.
- What product changes the technology requires.

” *One of the great paradoxes is that these complex systems can usually be justified only when a new product is launched*” [Ettlie, 1986]. This is probably true also in the case of FAA system where the possibility to introduce a well functioning system to use with existing products are very limited.

The fact is that introducing a new technology takes time, and time means changes in a high paced market environment. In the study by *John E. Ettlie* performed in the mid 80's, one of the studied cases had as little as 65 % of its original product parts, originally scheduled for the system, still present when the manufacturing system was “up and running” [Ettlie, 1986]. There are reasons to believe that there are even less than 65 % if the study was to be performed today. This could be seen as a proof of the fact that a product is a moving target and, since flexibility has its limits, if one do not take these changes into account one could end up with the “wrong” system [Johansson & Erixon, 2002].

User strategy

User strategy is mentioned as an important variable in the success of implementing a new technology. The key to this variable seems to be the planning horizon - the longer the better. Another important factor is the degree to which manufac-

turing is a part of the long range plan. *Yxkull* talks about the importance of a long range plan for both the assembly system and the product in order to facilitate the use and economical justification of FAA-systems [Yxkull, 1994]. Sony is another example on a clear user strategy [Makino, 1993], [Kimura, 1991].

Incremental implementation strategy

It is wise to take a strategic approach to implementation and allow sufficient time to implement. It is equal important both for the people involved and financial resources [Ettlie, 1986]. This is especially true for small medium sized companies [Onori et al., 2000]. Therefore, one important factor for a successful implementation of a new technology is whether it is possible to implement it in incremental steps. One of the keys to a successful implementation must therefore be the degree to which a technology represents a radical as opposed to incremental departure from an existing practise at the actual company.

This may be one of the reasons for why FAA systems have not been installed as widely as was anticipated in the early 90's. Some of the difficulties are related to the fact that the FAA-systems do not permit some of the manufacturing- and product design processes, an incremental departure from an existing practise. For example, one cannot gradually change a product design to facilitate automatic assembly because, the FAA-system complexity gradually have to change from high complexity to low complexity. The reason is that products not designed for automatic assembly often needs complex system solutions and an initially complex system can spoil the idea of stepwise implementation due to low return of investment(ROI). Instead every system installation step should have a reasonable ROI to be able to support the next step. This can only be achieved with a frog-leap in product design [Johansson & Erixon, 2002].

The reasons for an incremental implementation are mainly cost and knowledge. It is often too costly to implement a new technology (as an FAA system) "on the spot" and the in-house knowledge needs to be increased. The stepwise implementation approach gives the company time to adjust to new circumstances. However, this stepwise incremental implementation requires time, and because of that, there are also some risks involved with an incremental implementation. The fact that it takes time means that circumstances may be changing during implementation, which in turn, means that the goal for the implementation is changing during the implementation. In other words, the targeted FAA system may be out of date.

In the beginning of this section the FAA mindset was mentioned as something that appears when the company understands the FAA technology and its effects on other areas in the company. The author believes that an installation of an FAA system when the FAA mindset is already in the company is a quite different situation than installation of a physical system without the FAA mindset. Therefore the system requirements posed on a system depends on where in the implementa-

6. REQUIREMENTS AND THE PROPOSED NEW APPROACH

tion phase a specific company is. A system considered flexible for one company can be a catastrophe for another, depending how well they have streamlined their product design to fit the actual FAA system approach. A good example of this is Sony [Kimura, 1991].

General management support

To have the management support is crucial in order to implement a technology such as FAA. It takes a lot of efforts, in both design and manufacturing, in order to achieve a well functioning and highly reliable FAA system. It is not possible to make such an effort without support from management. Support, however, must be differentiated from involvement; support is essential but involvement limits success [Ettlie, 1986].

Participation

Participation for the potential system users is an important part in a successful implementation. However in order to be able to participate there is a need for training. A minimum amount of knowledge about a significant, radical shift in technology is necessary for people to be even adequate participators. *“involvement of the users increases the possibilities for a successful implementation of the equipment and for the operators to take on greater responsibility...”*[Mårtensson, 1995]. The ideal situation would be that the users of the system could take part in the design of the equipment.[Mårtensson, 1995].

Justification

It is very seldom possible to justify a new technology by the reduction of labour costs and other unit production costs. This was shown in the case study and has also been experienced in other projects [Langbeck, 1998]. *“..It should be noted, however, that these advanced manufacturing technologies seldom save money; they provide new opportunities to make money”* [Ettlie, 1986].

Size, structure and organisational culture of the company

The size, structure and organisational culture of the company seem to have some correlation to how well a company adopt a new technology. The interest from management and the overall level of fear and resistance to change are probably important factors. The size of the company could in a way determine the amount of resources that can be used for the implementation where large companies tend to have more resources to set aside for R&D The case study clearly supports this and was also discussed by Onori [Onori et al. 2000].

Training

The training of the users of a manufacturing system is another important factor for a successful installation. Training involves skill areas –for example programming, operation and maintenance. Further, it is important with early commitment

to training and education, as it is perhaps the most an important factor in establishing a readiness for change and participation. *“Investing a lot of money in a highly sophisticated equipment does not pay off unless the staff gets a proper training [Mårtensson, 1995].*

The author’s beliefs are that the implementation of a new technology incorporates more than just training of key persons such as operators and maintenance personnel. To implement new technology one must learn and understand the principles for the technology, which means education rather than training. With gained understanding it is possible to utilise the advantages at all levels of the company. If the principles are understood the system can be more “alive” and the company can, with in-house efforts, change the system settings to adjust to the new goals. This is especially important in the case of complex FAA systems where changes appear more frequently than in FMS systems.

Training would not be too intensive if there were reasonably standardised systems as in the case of FMS-systems. However, in the case of FAA systems where there are no real standardised ways of building systems, and the installed system often have a supplier for each sub-system, the training for the whole system could be an intricate task.

In the case of education, larger companies can often afford to have in-house competence for most of the sub-system technologies and therefore actively participate in the building of the system. However, small companies are totally in the hands of the vendors. In other words, -larger companies have the ability to keep a broader educated staff and thereby have a lot of the technology understanding in-house, and the education effort is not so intense. Small companies as shown in the case study have to educate themselves in the system technologies during installation. The training can be done by the vendor, but the understanding through education implies either employ educated personnel or learn by doing.

As a part of the understanding of the technology, one must understand how this new technology affects other areas of the company. The new technology will pose new demands on other activities, such as design. This is a very important issue in the case of automatic assembly. If one understands the principles of the technology and how it affects other areas in the company it is possible to derive a strategy for the future development of a system built on these principles.

6. REQUIREMENTS AND THE PROPOSED NEW APPROACH

The above factors can in the author's opinion be summarised in the same way as the case study:

Learning the technology:

- Supplier-user relationship
- General management support
- Participation
- Size, structure and organisational culture of the company
- Training

Product design:

- Product – process dependency

Strategy for implementation:

- Incremental implementation strategy
- User strategy

6.2 Ensuing System Requirements

In order to facilitate implementation of FAA into small companies, the FAA system hardware has to support the findings discussed in the case study and in the previous section.

In order to do this the author propose that the FAA-hardware solutions have to:

- Support a stepwise introduction of the technology.
- Be able to hide complex technology behind a user-friendly interface.
- Give clear product design guidelines. (i.e process driven design)
- Support a proactive strategy instead of a reactive (more static flexibility).
- Enhance the possibilities for prioritising of the flexibility efforts
- Consider the degree of optimisation of an FAA system

Due to the small companies initial lack of competence, financial situation and limited personnel resources to set a side for an implementation, the system has to be built stepwise while the company learn the technology. Often the small company does not have the competence required, and in case the competence exist in the company, the person or persons that have the competence are too occupied with daily issues in order to participate in implementation. Figure 41 shows the relation between competence and resources as perceived in the case study. The stepwise installed system components have to gradually increase the profits in order to finance the next step. *“Application of these techniques benefits from a step-by-step*

approach” [Mallin & Sacket, 1984]. In the case study there was an over-belief in the system and process capabilities and, at the same time, it was hard to motivate product changes before the system clearly showed its limitations. A step-by-step implementation approach would be preferred to avoid a too product specific system solution. I.e. product and process should meet half-way. When FAA is implemented it would be more natural to let the process guide the designers. An example of this is Sony and their Sony Smartcell [Kimura,1991] [Fujimori, 1990] [Makino, 1993]. Figure 42 shows different approaches to FAA implementation using Ulrichs product-process matrix as a base [Ulrich 1995]. A conclusion of this is that

The system should be structured and configured in a way that the border between manual assembly and FAA is not sharp and definite. A sharp and definite border results in large one-time decisions and huge strategic choices. Such definite decisions imply a complete change of direction and there is a high risk of failure along the way. If on the other hand, the border between FAA and manual assembly where to be more diffuse, the balance between manual assembly and FAA could be reached incrementally. Balance means here, the balance between technology and competence. During an implementation a lot of things can happened to the company, its products and market, a stepwise incremental approach reduces the risk. *Heilala& Voho* also propose a stepwise automation approach although they are mainly focusing on semi-automatic systems [Heilala & Voho, 2001].

		Competence	
		Not available or limited	Available
Personnel resources	Limited	Totally in the hands of the vendors or system suppliers. - Needs a turn-key solution	Have the ability to monitor and participate in decision making
	Available	Have the possibility to participate and learn during implementation	Possible to build system in-house - Total control of the evolution of the system

Figure 41. The relation between competence and personnel resource as perceived in the case study.

6. REQUIREMENTS AND THE PROPOSED NEW APPROACH

Also from an economical view there has to be a balance between manual assembly and FAA, this balance would also benefit from an incremental approach. The case study showed the need for a way to quickly build a simple system for testing and if the system works, quickly move to full-scale assembly.

The system should be guiding the designers on how to design parts and products in order to get the most effective assembly process, a process driven design. This would be accomplished much easier with a standardised system approach where the capabilities are known to the designer. In this way the system will be proactive instead of reactive [Johansson & Erixon, 2002]. A conclusion that can be drawn from this is that there is not possibly to use FAA if the company does not have control over the product development.

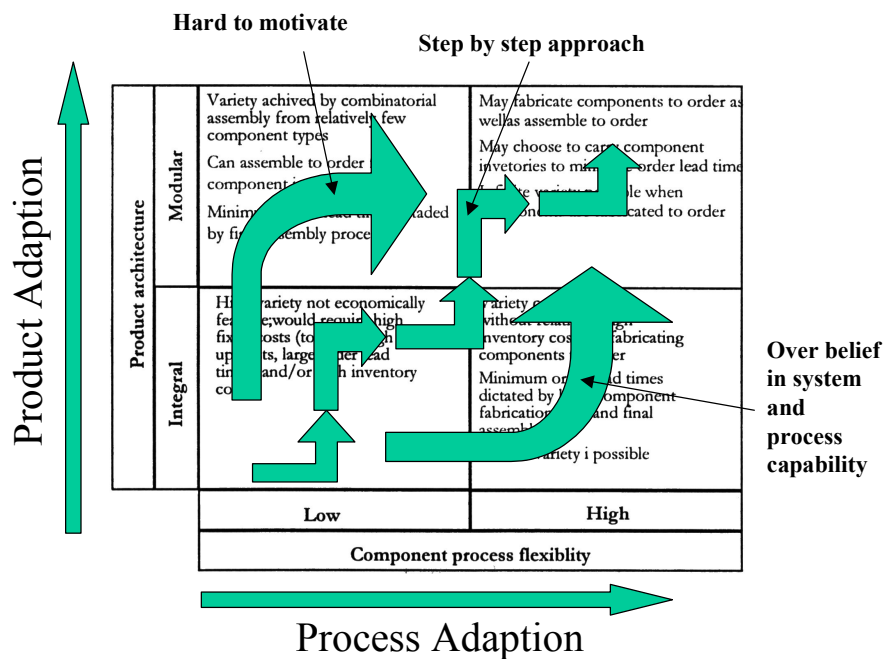


Figure 42. Different approaches to product adaption vs. process adaption using the matrix from [Ulrich 1995] as a base.

Flexibility is strongly required in today's manufacturing, but it is also very costly. During the implementation of FAA the small company would benefit if it were possible to prioritise the flexibility effort. If it were possible to stepwise focus on the currently most required flexibility in each step of the implementation and system installation, the steps would perhaps be easier to motivate and justify. Similar thoughts have been presented by [Gröndahl & Onori, 2000].

Another important thing to discuss when implementing FAA, not only into small companies, is the level of optimisation. The idea is that it is possible to reach a certain flexibility in more than one way. In markets with short product-lifetimes the fast changes of the system and quick ramp-ups are more important than an optimal performance during run-time, i.e. products per hour. The gain by using an optimised performance can be lost by a late product release as discussed in chapter 1, Figure 1 [Smith & Reinertsen, 1991].

The following sections details what has, and what must still, be done in order to fulfil the above requirements.

In order to accomplish what was discussed in the previous sections, the author proposes some new thoughts and approaches. Furthermore, the author intends to perform further research in the following areas:

- Prioritising of flexibility efforts.
- Modular assembly systems.

6.3 Flexibility, an applicable definition

As stated earlier, flexibility, instead of the actual assembly process, has been the core issue of most of the FAA developments to date. This fact has been further aggravated by the fact that a firm grasp of which type of flexibility is being targeted has been neglected in favour of a general, yet vague, description of this term. The author therefore presented a new definition, which intends to facilitate the understanding of the underlying potentials of the FAA system in question. This definition is further analysed in this section.

As discussed in previous sections there is a need for small companies to be able to prioritise their flexibility efforts. Research has to be done to develop a method to determine what flexibility is most important for the company and thereby be able to prioritise the efforts.

In chapter 3 a vast amount of flexibility concepts and terminology were presented. A way to structure the flexibility concepts is to approach the problem from the different horizons and frequencies that the different types of flexibility imply. Another way to structure the flexibility concepts is to match the different flexibilities to where in the different life-phases of a product or assembly system they belong. This frequency and horizon approach and life-phase approach has been combined into a “flexibility map” [Johansson & Erixon, 2001].

6.3.1 The Flexibility Map

Structuring the different concepts of flexibility according to their scope, i.e. range of processes in an FAA system, in a “flexibility map”, gives a clearer view of the meaning of each concept, Figure 43 page 129 [Johansson & Erixon, 2001].

On the axis at the bottom of the “flexibility map”, the different process levels in an FAA system are plotted from left to right according to their frequency of appearance and horizon in the system. On the left the frequency is high and the horizon short and the focus in the system is “doing things right”. Moving gradually to the right, the frequency for the processes decreases and the horizon increases. On the right side, the focus is on “doing the right thing”, the FAA system is merely a concept and decisions are strategic. The processes on the scale are common processes that appear in an FAA system¹⁵. Each of these processes needs to have a certain ability to react upon changes. For example, on single operations level, the system processes has to adapt to differences in geometrical shapes and part tolerances. On batch level, the system must have the ability to swiftly change between batches and shift operation sequence within a batch. On order level, the system must be able to shift between different orders and change order priorities to handle for instance an express order. The ability to quickly change between planned variants without long set-up times is a flexibility called for on planned variant level and so forth. The “grey zone” in the middle of the map represents the border between dynamic- and static flexibility, where dynamic flexibility is on-line flexibility and static flexibility is off-line flexibility. This border is not definite but depends on how flexible a system should be for a certain situation. It is a priority matter and depends on individual company needs.

In the “flexibility map” the flexibility concepts mentioned in literature are plotted as white “boxes”. The horizontal size of the “boxes” represents the scope of the described concepts within the FAA system life-phase. This is not to be considered an absolute measure, but as a schematic outline. The height of the map is of no significance, i.e. the concepts are not put in any specific order vertically. The horizontal size of the boxes in the map shows how general a flexibility concept is. A general flexibility concept tends to be un-precise and of little use. In the case of FAA systems, connecting the various operations performed in the system to the actual product-life cycle gives a clear view of the horizon for various flexibilities. Adding frequency as another factor could help in prioritising various flexibilities as will be explained further on.

¹⁵ A more stringent classification of the sub-processes involved, and their relation to the design process and existing equipment, should be investigated [Tichem et al., 1999].

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

Table 13. Translation table for the references in the flexibility map Figure 43.

Author	Reference	Author	Reference
Andreasen	[Andreasen & Ahm, 1986]	Gerwin	[Gerwin, 1983]
Björkman	[Björkman, 1990]	Johansson C.	[Johansson C., 1981]
Bodine	[Bodine, 1993]	Landqvist	[Landqvist & Papinski, 1983]
Browne	[Browne et al., 1984]	Tichem	[Tichem, 2000]
Chrysosolouris	[Chrysosolouris, 1996]		

6. REQUIREMENTS AND THE PROPOSED NEW APPROACH

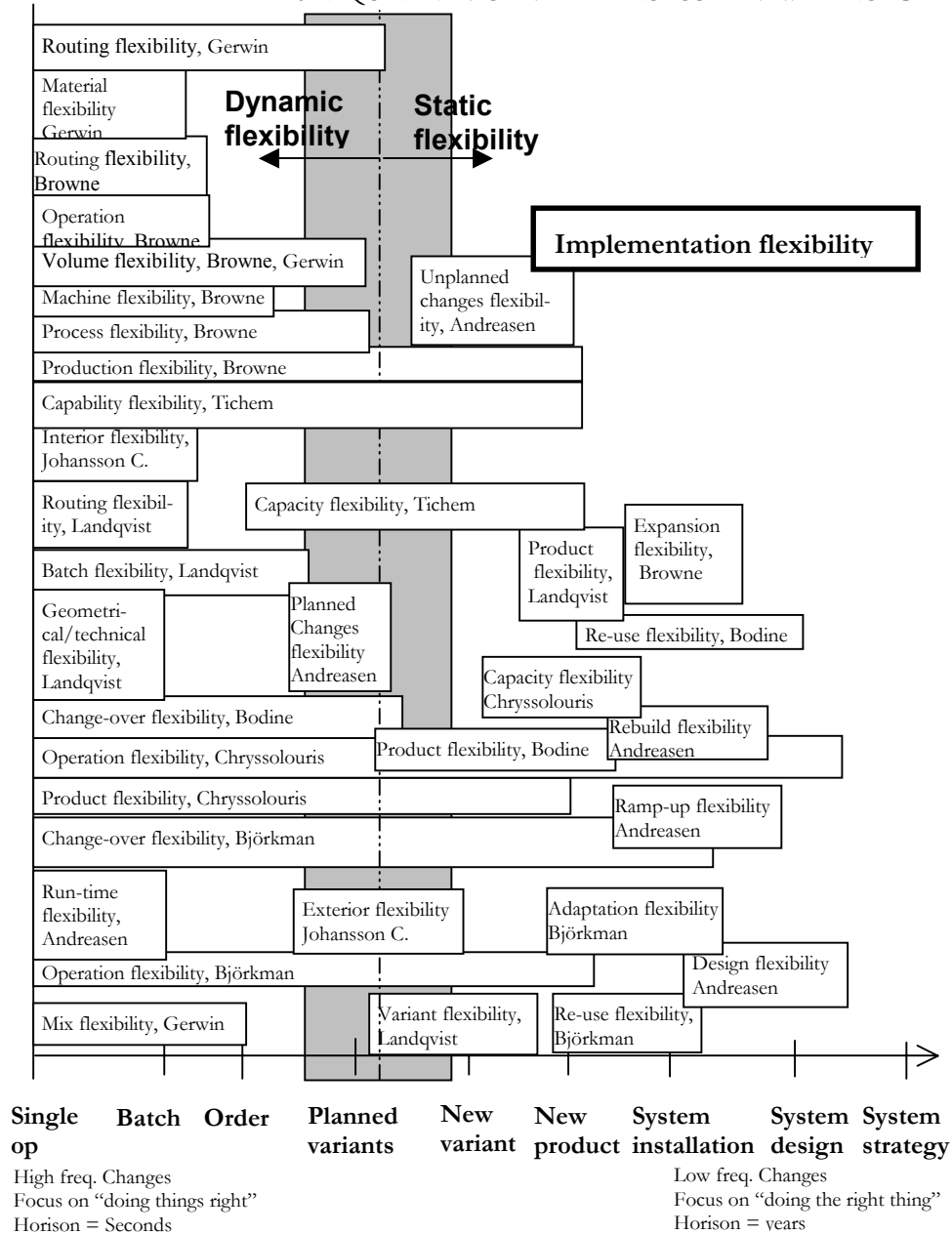


Figure 43. Flexibility terms found in literature structured schematically according to their focus in the assembly system life-phase [Johansson 2001]¹⁶.

¹⁶ Tichem’s contribution has been discovered after the publication.

6.3.2 Implementation flexibility

In the above flexibility map the concept of implementation flexibility is introduced. This flexibility is defined as the system flexibility that allows for:

- ...the ability for the user to achieve, in a stepwise manner, a level of "sufficient flexibility" (see definition of penalty of change) by focusing, in each step, on the most important flexibility issue.
- ...a stepwise introduction of the technology.
- ...that the balance between manual assembly and FAA could be reached incrementally.
-the assembly system status to be kept in phase with the product status since during an implementation, a lot of things can happen to the company, its products and market

If all these above demands for change can be accommodated without an unreasonable penalty, as will be explained in the next section, the system is considered to have implementation flexibility. This flexibility is defined in order to pinpoint the certain problems that may occur during an implementation of FAA, i.e. until the company has reached a competence level and FAA-mindset that allows them to have control over product and system development. Note the difference between installation and implementation as explained earlier. When the company has the FAA-mindset the system work will be more concerned with installation.

6.3.3 Flexibility and its priority

Flexibility is important, but there is a need for prioritising and selecting what type of flexibility to incorporate in a system. This is especially true in small companies where, due to financial and competence reasons, a bad decision can lead to disaster. This decision should be based on the ratio between the cost of achieving flexibility and the penalty of not having it. The flexibility measure defined as penalty of change [Chryssolouris, 1996] as presented in chapter 3.2 will be used as a base. *High* flexibility is equal to *Low* penalty of change. Penalty of change is defined as:

$$POC = \text{Penalty} \times \text{Probability}.$$

A system can be considered producing as long as it is in a steady state. When the system gets unstable (loses focus), the penalty for achieving steady state determines the flexibility. The flexibility focus should be on the system processes that have highest penalty of change.

By combining the flexibility map and the definition of POC, a discussion concerning what flexibility is most important, for a specific case, can be made. The penalty is, in the end, the cost. The immediate penalty is seen as decrease in

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penalty is, in the end, the cost. The immediate penalty is seen as decrease in throughput and increase of storage according to the theory of constraints [Goldratt & Cox, 1989]. The cost should not be too hard to determine. For example, it would not be hard to estimate the rough cost of a missed order due to lack of flexibility. The major problem is to determine the probability for the change demand at each process level in the flexibility map. One must then account for the probability that something happens at single operation level that would need the system to handle change or, at the other end, the probability to make a false strategic decision that would call for the system's ability to be easily changed. The idea is to focus on flexibility where the penalty of change is highest. If the probability for a change were the same for all process levels, then the obvious choice would be to focus on static flexibility concepts for the system. On the other hand, if the probability for a bad strategic decision is very low, the focus should be on the flexibility concepts more to the left in the flexibility map. Looking at the dynamic flexibility area in the "flexibility map", it can be assumed that the penalty of change increases from left to right. This implies that an assembly system should be arranged in a way that failures in high frequent processes should not severely affect a process with lower frequency [Johansson & Erixon, 2001]. The curves in Figure 44 are merely examples. Each process in the flexibility map would likely have an interval, for the probability for change demand, cost and thereby also the POC.

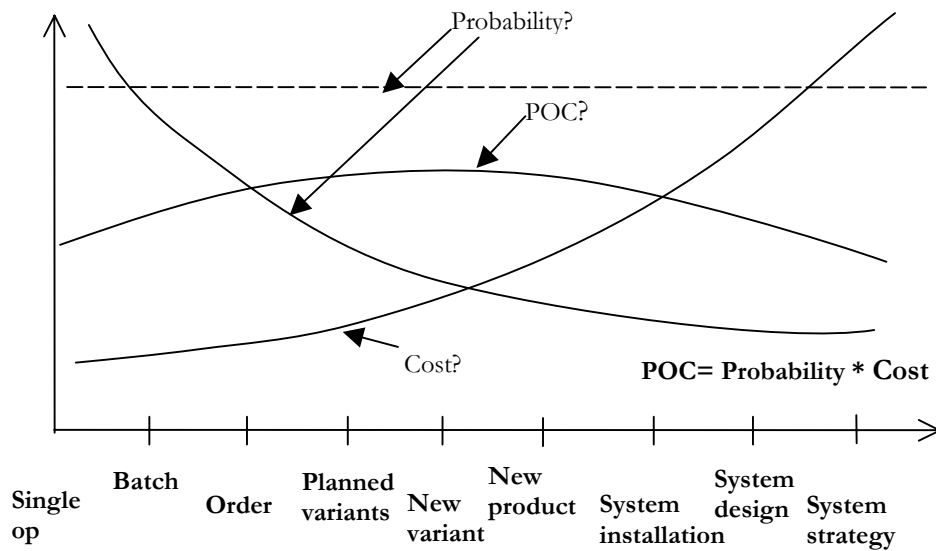


Figure 44. POC curve depending on probability and cost scenarios. [Johansson & Erixon, 2001].

The POC would to some extent be company specific and product specific. Even if these are merely example curves, studied cases indicate this [Arnström & Gröndahl, 1985], [Arnström & Gröndahl, 1988b], [Arnström et al., 1993].

6.3.4 Comments

The POC curve for an FAA system could perhaps be used for evaluating the system. Future research should focus on the generation of POC-curves in order to develop a decision tool when prioritising flexibility efforts.

6.4 Modular assembly systems

In order to facilitate implementation and installation of FAA into small companies a modular assembly system approach is proposed. This section intends to motivate why the modular systems is the best approach by introducing and discussing the advantages and summons up with future research that will be focused.

6.4.1 Static- vs. dynamic flexibility - A negative correlation

In section 3.2 a discussion about static- and dynamic flexibility was brought up. Furthermore, it was established that there exist, a negative correlation between static and dynamic flexibility [Allingham, 1990].

The negative correlation between static flexibility and dynamic flexibility is a problem and several research projects have experienced this, for example, [Arnström et al., 1993], [Heilala & Voho, 2001]. In the tendency to strive for high flexibility in the high frequent processes (see previous section concerning the flexibility map), i.e. have a high level of dynamic flexibility, the possibilities to reconfigure the system to new products, or even unplanned variants, decreases. This is due to the high level of specialisation and product specific equipment needed. A coupling tends to appear over the system, i.e. nothing can be changed without affecting something else. It seems like the effort to attain the last 20 % of dynamic flexibility spoils 80% of the possibilities for static flexibility.

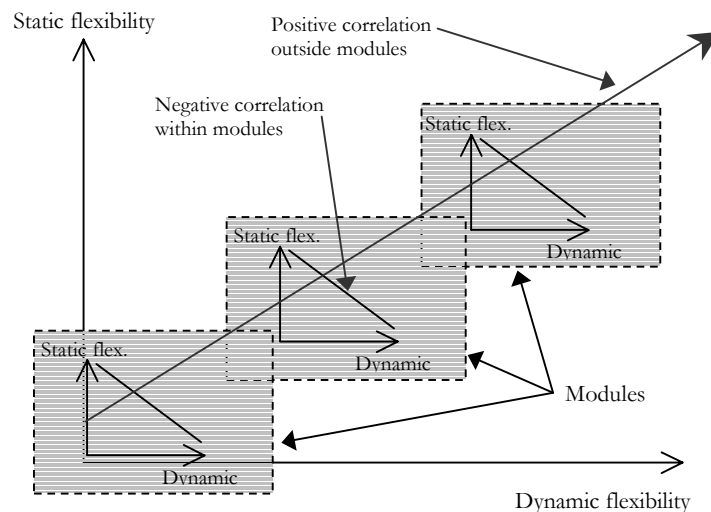


Figure 45. A diagram that shows how the negative correlation is kept within modules.

A possible way to decrease the negative correlation is to build FAA systems in a modular manner. In this way it is possible to isolate the negative correlation within modules and maintain static flexibility outside the modules, Figure 45. This implies the use of modules with standardised interfaces. Researchers at the Royal Institute of Technology, the author included, have discussed this for some time now and the Hyper Flexible Automatic Assembly (HFAA) project is partly a result of this, Figure 46, [Onori et al., 2000].

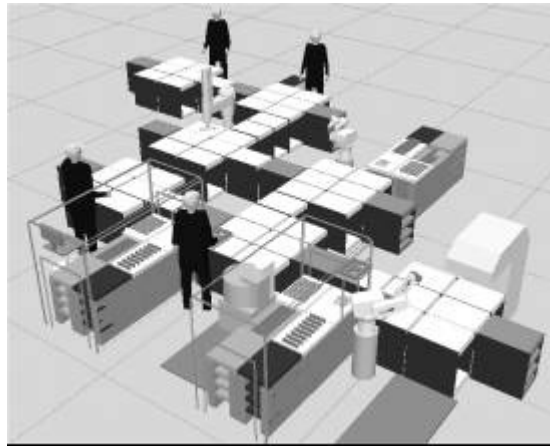


Figure 46. FAA-modules as shown in the HFAA project [Onori et al., 2000].

The modules can be designed from two perspectives or levels of abstraction. On the first level, modules are developed that handle a specific function within an assembly system. These functions are for instance transfer, transport, feeding or mounting. On the next level, the module is a small production unit (task unit), with above functions incorporated, handling the assembly of one or more parts. These two modular approaches are by no means a contradiction. The two approaches can be combined. The reason for the latter is ease of use. Due to lack of competence, the latter approach would be a great help for small companies. The “size” of the standardised production units is important since they would be the common unit, the least common divisor of the system. The modules must be at a reasonable cost in order to facilitate small stepwise investments as competence increase. The module approach allows for stepwise upgradeability of a system and moreover stepwise implementation, which is very important in small companies where the increase of competence and system complexity must go hand in hand.

Static flexibility is important in the effort to keep the assembly system status in phase with the product status. That is, in order to change the assembly system according to the product plans [Yxkull, 1994], the system must have the ability to be easily reconfigured or rebuilt. A modular approach with correct modular “size” facilitates this.

6. REQUIREMENTS AND THE PROPOSED NEW APPROACH

The HFPA project also details what may be interpreted as a shift in paradigm. The goal is not to focus on the development of a highly flexible machine or system. The goal is to create a flexible concept in which the individual components are optimised in terms of a given functionality and for a closed set of tasks and, thus, not very flexible in terms of functionality.

In order to achieve this, a serious effort to study and structure the assembly process itself is being carried out, see Figure 47

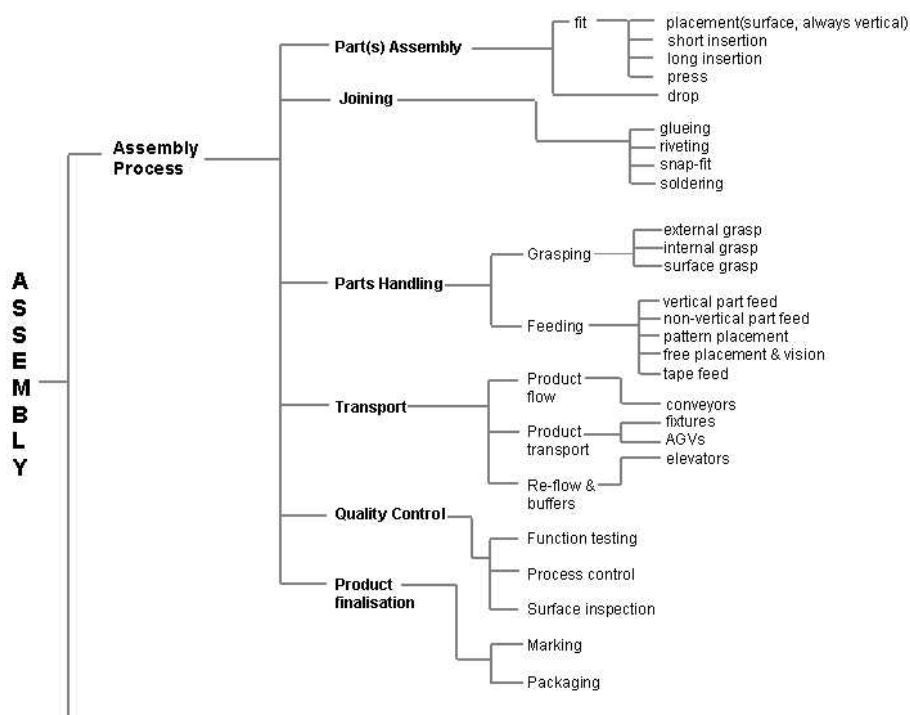


Figure 47 An effort to structure the assembly process, performed in the HFPA project. Picture is generated by prof. Mauro Onori at the Royal Institute of Technology, Stockholm.

6.4.2 Reducing the cost for flexibility over the period

Usually, FAA systems are developed and designed on the basis of an anticipated future where all flexibility that might be necessary during the systems life-phase is incorporated. As a result of this approach all flexibility costs will burden the system from the beginning even if not used until later (or perhaps, not used at all). Since investment calculations take the whole system into account over a certain period of time, the system must be run as originally built through the period, be-

cause of economical reasons rather than production reasons. With a modular approach, the investment calculation can be on a modular level and flexibility, or capacity can be incorporated when appropriate. Justification on module level should become more accurate and the time delay between cost and revenue should be reduced. Figure 48 shows an example of how a modular stepwise approach may reduce the gap between cost and revenue. Note that the curves are merely schematic outlines to show the reasoning and are not yet scientifically verified.

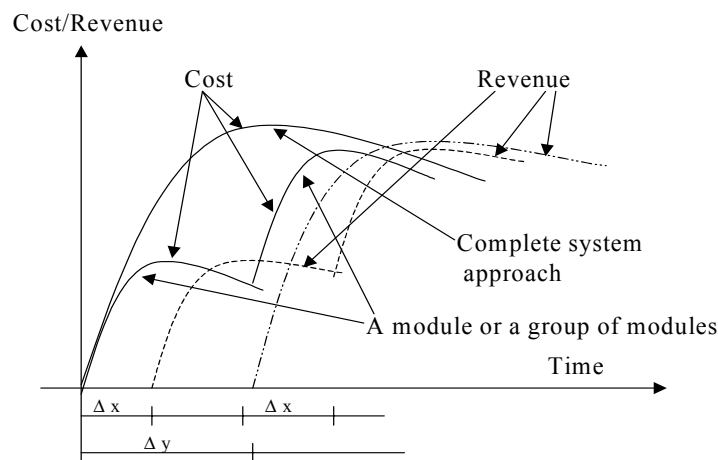


Figure 48. An example on how a modular stepwise approach can reduce the gap between cost and revenue [Johansson & Erixon, 2002].

Another leading idea in the modular approach is that one should be able to learn from the previous installation and thereby decrease the cost trend for installation and change. It is an analogy to the efforts made to reduce programming cost by using a modular approach to programming [Onori, 1996]. Engineering cost is an important share of the development and installation costs for an FAA system. By using a modular approach in, for instance, an increase of capacity, where standardised modules are duplicated, most of the engineering cost will fall upon the first module. Figure 49 shows schematically how cost may be decreased through different development steps by using standardised modules. The difference $Y_2 - Y_1$ is due to reduced costs in education/training, engineering, better product structure, less resources needed for installation etc.

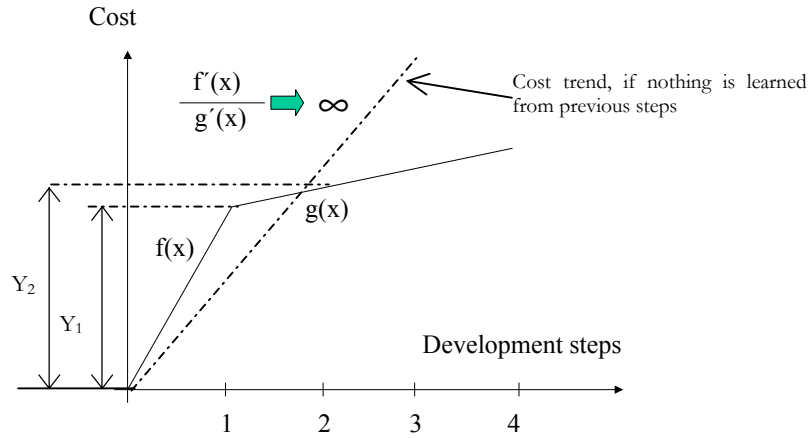


Figure 49. A schematic view of a decreasing cost when using a modular approach
[Johansson & Erixon, 2002].

6.4.3 Standardized modules instead of systems (module level instead of system level)

A modularised assembly system with standardised modules, and standardised interfaces between modules, makes it possible to configure systems to various needs. Contrary to the standardising of whole assembly systems, the standardisation should be on a module level independent of the system itself. In this way one could build a number of standardised systems using a bottom-up approach, i.e. building systems by putting appropriate modules together. The design of the system must still be done in the top down manner, i.e. identify the needs and choose the appropriate modules. As long as there exist no standard modules to build a system upon, there will always be companies that try to gain production advantages by developing their own systems. After all, there are no alternatives. If there were to be standard modules to build systems upon there would be a substantial decrease in ramp-up times and, therefore developing systems from scratch would no longer be a good option in changing markets [Johansson & Erixon, 2002].

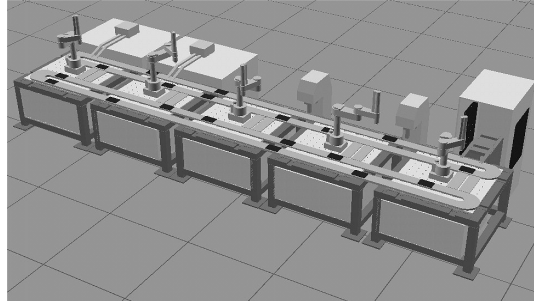
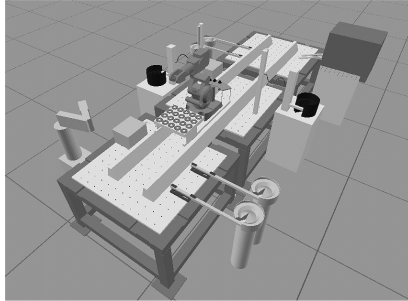


Figure 50. The previously described Mark III system built with modules. (Picture generated in the HF_{FAA} project by Prof. Mauro Onori at the Royal Institute of Technology)

Figure 51. The previously described SMART system built with modules. (Picture generated in the HF_{FAA} project by Prof. Mauro Onori at the Royal Institute of Technology)

6.4.4 An educating system

As identified during the case study, and spelled out in literature, the competence of the company personnel is an important factor if to be successful in implementing a sustainable FAA system. The installation in itself is possible to perform with competence from outside the company but when the system is up and running and the hired competence leaves, the system will become a “dedicated” system for the products for which it has been configured. Since the personnel that will work with the system often know, or understand, only a limited part of the system the ability to improve and reconfigure the system for future products are limited. This means that a main goal in using FAA systems is lost.

A way to facilitate implementation into a company with little competence is to develop system modules that incorporate one or several standard functions (task-modules) and at the same time hide complex technology behind a user-friendly interface, a kind of “encapsulated knowledge”.

By building assembly systems consisting of standardised modules the need for immediate specific knowledge could be reduced. The idea behind this is that, by learning what different modules actually do and how to install them, the ability to reconfigure the system for future products will be less dependent on specific knowledge on component and process level. New modules with new technology can in small steps be introduced to the operators. The author believes that it would be proper to introduce the technologies in reversed order of complexity. That is, first modules that automate the transfer process then the transport process and then finally the more complex technologies, the feeding- and mounting process. During runtime the personnel can gradually learn the system principles without delaying the ramp-up of the system. Small companies cannot financially endure the learning period if it cannot be performed in parallel with production.

Further more, with standardised modules product design can to a greater extent be more process driven and thereby teach designers to come up with DFA-solutions. In this way the system can be more proactive than reactive.

6.4.5 Technological adaptability

A modular assembly system is simpler and cheaper to adapt to a new product technology. It is simpler and cheaper due to a clearer border between different functions or tasks in the system. As opposite to a none modular system there is not connections throughout the whole system. The system is more uncoupled. Therefore, it is possible to change certain properties or change parts of the system without affecting the whole system.

6.4.6 Small and big companies, same demands on module level

A main and leading idea concerning the standardisation and modularisation of the FAA system is that on module-level the demands are the same for large and small companies. That is, on module level there exist common system needs and because of this the market for standardised modules should be larger than standardised systems. This is also confirmed by a study made by *Frost & Sullivan* [Frost & Sullivan, 1999]. With a larger market the installation costs could be reduced and FAA more spread. If the only difference in system demands between small and large companies, concerning the actual production is capacity, excluding competence and economy discussed earlier, the common unit (the “least common divisor” discussed in chapter 4) could be duplicated in the large company while used more restricted in the small company [Johansson & Erixon, 2002].

6.4.7 Avoiding to invest in dead ends

An important factor when discussing implementation and installation of complex systems such as FAA systems is that it takes time and the market and product are in fact changing during implementation. The product is a moving target and flexibility has its limits. *“unexpected changes will occur during FAA system projects.....from this perspective another important conclusion is: Be prepared for changes arising in specifications during the project”* [Holmstedt,1998].

In times of change you need options, too much dynamic flexibility for example, as discussed earlier, will decrease the systems ability to adapt to the changes not planned for. A modular approach will increase the possibilities to react on changes during installation. You may not have to do all the right decisions from the beginning with a modular approach. Due to the modularity the system can be expanded and changed more easily. *“A common view is that “we could have planned the installation better”, rather than maintaining a controlled flexibility during implementation.”*

[Ettlie, 1986]. Short pay-off times reflects uncertainty in investments decisions, short pay-off times makes it hard to economically justify complex FAA systems. A modular system approach that supports stepwise implementation and installation can lead to:

Shorter planning horizon = more secure decisions = longer pay-off times allowed = easier justification.

It is a common opinion that the development of product and manufacturing system should be performed in parallel. However, in a fast changing market the product may change fast and therefore, for economical justification reasons, the manufacturing system, in this case the assembly system must live longer. A modular approach could probably facilitate this. The leading idea concerning this is:

Product life span \neq Assembly system life span.

Instead the modular idea is:

Product life span = Assembly system module configuration.

A system is one or more modules put together to perform an assembly of a product. A module can consist of manual operations if suitable. By using standardised modules it is the configuration of these modules that have a life span similar to the product life span. In some cases the module is perhaps not suitable for the product to come and must therefore be discarded. With a standardised module approach discarding may not mean that the rest value for the module is low. Instead the module may be interesting for other manufacturers. If not so, as discussed earlier the economical justification, investment calculation, can be performed on module level and not affect the whole system.

6.4.8 Short ramp-up versus optimised systems

Another leading idea concerning suitability of a modular approach is that in a fast changing market the use of an optimal system must be put in relation to the possibility of a short ramp-up.

As seen in the previous study of flexible assembly systems in chapter 4, it is possible to focus on dynamic flexibility or static flexibility. The most common approach in the effort to attain a flexible system is to build a totally integrated system with a large portion of optimisation, to handle various situations that could be foreseen, and thereby planned for., see for instance Mark II [Arnström & Gröndahl, 1988a]. Optimisation is often towards a low cost/capacity ratio for the period foreseen. Another way to attain a flexible system is to build the system divided in modules with certain operations assigned to each module (task oriented). The system as a whole is in the latter case not optimised for the situations it may have to handle but still, in most cases it can do so anyways. The system is

thereby not optimised for a closed set of tasks that can be foreseen; instead, the modules are optimised for a closed set of tasks. The system as a whole is instead optimised concerning cost/capacity for a long period of time not possible to entirely foresee. An integrated system (non modular) can be seen as a sub-optimised system when looking over a long period of time since it is optimised for the short period that can be foreseen. The modules must, in a way be generic, by which means, that the modules are optimised as in tailored for a well-defined task, although, not specialised for 100% reliability of one single task. When using a modular approach the sub-optimisation is strictly limited to within exchangeable modules. This should be a good idea since there are seldom whole systems that need to be changed when introducing new variants or new products. The POC discussed earlier is thereby isolated to modules. In the modular approach “strength” is used rather than “fitness”, i.e. by using several identical modules instead of one optimised system the system can handle the situation but not in an optimal way. Systems that use “strength” instead of “fitness” focus more on the possibility to change the system to new situations, static flexibility.

In markets with fast changes in products, there is no use in optimising the system too much, since the time it takes will make you second on the market. The cost for being second on the market will not be covered by an optimal system. Instead one should try to build a system that uses standardised and well tested processes that are robust and dimension the system with over-capacity. This is in-line with the words spoken by [Suri, 1998] as he proposes ways of shorten lead-times.

6.4.9 Concluding remarks

In previous sections a modular assembly system has been discussed and some leading ideas were presented:

- One should be able to learn from the previous installation and thereby decrease the cost trend for installation and change.
- On module-level the demands are the same for large and small companies, therefore, standardise modules instead of systems.
- Product life span \neq Assembly system life span.
Product life span = Assembly system module configuration.
- Short ramp-up vs. optimised system

The above leading ideas must be further investigated and verified in order to motivate further work with the modular approach. In addition to this, some research will be performed in order to connect flexibility issues to module level. As discussed before, small companies needs to prioritise their flexibility effort. To facilitate this it would be of big interest if modules could be matched to the flexibility

needs (see the flexibility map, Figure 43). A question that comes to mind is then: Is it possible to connect certain types of flexibility to certain assembly key processes and based on that, prioritise a certain set of modules depending on the flexibility need? This should be investigated further and scrutinised.

An important issue perhaps not emphasised enough earlier in the thesis is that a prerequisite for the use of FAA-systems is that the company has control of the product development. This is due to the importance of DFA (Design For Assembly), since a badly designed product will definitely create product specific and costly assembly solutions, as was discovered in the case study. The product design process is without saying important when using FAA-systems. Further research should therefore focus on creating a dynamic link between the proposed standardised modules and the product design process in order to create a process driven design. In order to do that the assembly process must be thoroughly studied and structured [Onori et al. 2001]. Based on the structured assembly process standardised modules can be created and the ideal scenario of a standard set of assembly components with specific process specifications would be attainable. Consequently, the designers can then through the dynamic link know in advance during the design phase if there are modules available and which constraints they pose on the design.

Future research challenges are therefore:

- Create a link between product design and assembly system components [Tichem, 1999].
- Standardised Interfaces
- Create assembly process oriented system components.
- Further develop the method on prioritising flexibility and degree of automation outgoing from the proposed POC-curve. A decision tool that can indicate when “sufficient” flexibility for certain type of product and production strategy is achieved.

This work has already started in a project carried out by The Royal Institute of Technology, the WoxénCentrum and Ericsson [Sandin & Onori, 2002]. The author has contributed in the creation of the requirements and actively participated in the HFAA project, which grounded the foundations of the Woxén/Ericsson project.

7 CRITICAL REVIEW

In this chapter a critical review of the work done so far is presented. The research structure and scientific approach is discussed and finally the objectives of this thesis and whether they have been met.

7.1 The Research Structure

The research in this thesis has been focused on FAA implementation problems, primarily those concerning small companies. Too little research has been done about the suitability of FAA in small companies; therefore, a more thorough analysis should be made on how the situation is for small companies.

The research work started with a clarification of some of the main terms used within FAA:

- what is meant by an FAA system,
- what is meant by flexibility and its many classes,
- a proposal for a new, more practically viable definition for flexibility,
- and, finally, a definition of the basic assembly processes to be accounted for.

From this point on, the thesis could have focussed on a more elaborate and well classified definition of the assembly process. It could also have focussed on the basic elements concerning a successful implementation of such technologies. However, the aim was to point out that the approaches, definitions and solutions used today do not satisfy the requirements of SMEs and, thereby, propose a new approach. Hence the pragmatic approach.

The work described in the thesis has therefore followed a pragmatic structure where the inherent terms within FAA have been analysed such as, flexibility and the assembly process aspects. Since FAA systems most often offer to be flexible solutions for production scenarios most common in small-to-medium sized companies, this thesis approach should be deemed correct. That is, if FAA solutions fit the demands of companies with limited budgets and competence, they should have greater chances to succeed in large companies. The reason for this being that the short product lifecycle and large product variant scenario, with rapid ramp-up and ramp-down features, is now commonplace in such companies as well.

7.2 The Scientific Approach

The work conducted in this thesis falls within the area of applied research. Although required, a stringent scientific methodology is not always applicable to

relatively new fields of research and development. This may create a basis for critical discussion, even though the author has attempted to follow a given approach.

The analyses have been conducted theoretically, by studying proposed FAA solutions, and empirically, by attempting to install an FAA cell in a small company. Both studies analyse the process requirements in terms of the attainable flexibility. Hence the need to present the proposed flexibility map.

The conclusions are drawn based on the two studies detailed above, and are detailed in relation to industrial and academic implementation studies.

The proposed flexibility definition is also detailed in the results with the efforts to propose a method for prioritising flexibility efforts. The definition is hereby viewed as a proposed definition and further validation is expected from the research community. The definition is an important part of the proposed FAA hardware approach solution, since it forms one of the bases for the modular assembly system thoughts: finding the correct level of flexibility by a stepwise installation. The definition helps in establishing what is “sufficient” flexibility.

The proposed hardware approach, modular assembly systems, is based on the work carried out by the author on the HFAA project and, at a later stage, the Woxén/KTH/Ericsson project. The main contribution has been in terms of the stipulation of the requirements, a direct result of the studies carried out. The proposed hardware solution is based primarily on a truly applicable stepwise upgradeability of the FAA system. Obviously, a stepwise implementation/installation of an FAA system is only possible if one can control the future development of the product, a fact that was pointed out in the concluding remarks as well as earlier in the thesis.

Many of the small companies may, because of this, never be able to implement FAA. It was stated in the beginning of this thesis that in order to stay competitive in the global market the small company has to increase its technology level and competence [Bhattacharya et al., 1995], [Frost & Sullivan, 1999]. By doing this, the small company may climb in the supplier hierarchy, supplying solutions to functions in a product instead of merely discrete components made from enclosed drawings. For many of the small companies this is a large step and is not suitable for all. Therefore, the thesis does point out, at least, that a more thorough analysis of the small company situation should be performed.

7.2.1 The objectives of this thesis

The thesis was written in support of the following hypothesis:

Developing FAA-systems for SME's requires a fundamental review of the application of the term "flexibility" as well as more gradual technological and competence implementation phases.

The first phase of the project concerned the attempt to define and classify flexibility definitions and FAA systems. This phase included the proposal of a new flexibility classification, as an attempt to clarify the different forms of flexibility being offered by the different FAA solutions.

The theoretical study was performed in order to validate whether there are fundamental discrepancies between the intended flexibility and the actual application's adaptability to different problems. Where possible, the detailed FAA systems were analysed in terms of the static and dynamic flexibility definition proposed by the author. The latter was conducted partly in order to establish whether this definition could prove to be a better evaluation platform.

The empirical study was carried out in order to collect data concerning the real assembly needs and possibilities for a small company. The major issues here were to find out whether or not the small company strategies, economics, and competence levels would be sufficient for applying current FAA technology (covered in the theoretical study) and, if not, what the major problems would be. Finally, the information gathered during the case study should have confirmed or denied the conclusions drawn from the theoretical study.

The work therefore *aimed to* point out the following:

There are fundamental problems with what FAA system developers call flexible and what the users experience. The main problems reside in the weak understanding of the assembly processes that have to be accounted for, and their production scenario settings. Other problems were found to be that, although most FAA systems are to be considered flexible, they still demand rather large investments, high technological competence levels, and do not offer long-term flexibility.

The Proposed Definition:

The proposed static/dynamic flexibility definition appears to be valid in the context of the thesis, but does require a deeper validation. The time frames for the thesis work did not allow for an in-depth validation. Furthermore, this definition should undergo a thorough analysis by the industrial and academic community in order for a correct scientific validation.

The flexibility map did, however, prove to form a clearer picture as to which type of flexibility each FAA solution actually tackled. This approach to, and clarification of, the different flexibility aspects and their applicability in terms of "frequency of change" is novel and, with some further work, potentially useful.

The Theoretical Study:

The main purpose of the theoretical study was to form a reference frame, for the research to be performed, and point out the state of the art. Some questions that could be brought forward include:

- Have the problems associated with FAA system applicability been pointed out?
- Are the studied systems too old and outdated?
- Are there too many research projects and too few commercial systems?
- Has the state of the art been pointed out?

The systems analysed stretch over a wide range and time frame and includes both academic and industrial projects. The achieved flexibility as well as problems associated with each system have been pointed out and summarised. Of course, there may be different perspectives to the analyses, each of which could bring new data to the problem definitions. The work in the thesis has, however, pointed out that the main focus, and thus perspective, would be that of analysing flexibility issues in terms of the assembly processes to be accounted for. Product design, supplier aspects, and other perspectives are therefore not analysed in any greater depth.

The studied systems are from a wide time frame and may, to a certain extent, be considered old systems. However, the purpose of the study was to analyse process solutions contra flexibility solutions and gather up a knowledge bank to use further on, so the old systems have their place. For some reasons the research systems have been fewer in recent years and the development seems to be led by commercial system developers. Latter commercial systems include the Flexlink Automation Dynamic Assembly System (DAS), GWS Flexible Production System (FPS), and other very similar solutions. These systems are not true FAA systems and represent the modularisation and partial standardisation of manual assembly lines, including robotic cells for the automatic tasks. The SMH Automation Plug & Produce solution represents the only true FAA solution of interest, which has not been covered in this thesis. The system was omitted due to the fact that it was presented after the research work was concluded. Apart from this system, the research community has, since the mid-90's, focussed primarily on micro assembly and no new proposals have, to the author's knowledge, been published.

There exists, therefore, no excess of research projects in this subject. Furthermore, there exist few commercial systems that can be classified as true FAA systems. The state-of-the-art has not evolved greatly in the past few years, thus the material must be considered as valid.

The Empirical Study:

The development of an FAA cell for a small Swedish company represents a single case study. The data gathered from a single case study may be considered minimal, and that several case studies should have been conducted for a more stringent validation of the data gathered. However, the development of an FAA cell for a small company is a time-consuming project, especially when carried out by a single development engineer (the author). Since the author took part in all the phases of the project, from product analysis and requirement specification, to the actual implementation (as an observer during the implementation), an in-depth view of the mechanisms that affect a small company's decision making processes and their implementation difficulties, was acquired. The data from the single case study must therefore be considered detailed and correct. The project, nevertheless, would definitely have benefited from at least one more case study, since there is a risk that some of the results are company specific. However, through the contacts with colleagues and literature studies, the results have revealed to correspond with other researchers experiences [Mårtensson, 1995], [Onori et al. 2000].

The Proposed Approach:

Modular assembly systems have, as mentioned earlier, been considered earlier. The novelty with the HFAA project is that it proposes a shift in thinking since it implies that theoretically very flexible, multi-purpose cells will be replaced by a highly flexible concept consisting of several well-targeted but not, in themselves, highly flexible components. That is to say that truly modular FAA systems will no longer consist of general assembly machines, in which each specific assembly task may be inadvertently sub-optimised. Instead the FAA-systems will consist of a large set of small, interchangeable components with fairly dedicated tasks. The HFAA proposal has led to new research projects, such as the Woxén/KTH/Ericsson project on Evolvable Assembly Systems, and has also pointed out the requirement to incorporate mini- and micro-assembly equipment within this set of components. Needless to say, this work will require a major effort from the entire assembly community, primarily because it implies the creation of standardised interfaces, an issue that is a major hurdle to any further development. These issues have been brought forward within the Assembly Net network for Precision Assembly (European Commission Project No. G1RT-CT-2001-05039), and have led to the formation of Special Interest Groups and discussion forums.

The major criticism to the work detailed in this thesis may be that a narrow perspective was taken to the problem area. Issues related to the requirement specification procedures, product design requirements, and personnel/ergonomic aspects, were not analysed in depth. These issues could have been integrated within

the project if the author had taken part in a large-scale effort or project, which was never the case. It must be pointed out that the need to integrate these issues in order to successfully resolve the problems is in itself a new approach, probably a result of many unsuccessful attempts to produce an effective FAA system, and the knowledge acquired in the process. Finally, the thesis pointed out from the very outset that the focus would have been narrowed to a given perspective. The results are utilisable in future research and the hypothesis has been, in terms of the given perspective, answered: although research within FAA technology has decreased substantially in the past few years, there is a need to further investigate the flexibility aspects and implementation needs of such systems. The author therefore believes, and hopes, that some proof to such a demand has been provided.

7. CRITICAL REVIEW

"Minds are like parachutes - they only function when open"

IMPLEMENTATION OF FLEXIBLE AUTOMATIC ASSEMBLY IN SMALL COMPANIES

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