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Stephan Eskilander - Design For Automatic Assembly – A Method For Product Design: DFA2 2001

KUNGL TEKNISKA HÖGSKOLAN

TRITA-IIP-01-02
ISSN 1650-1888

Design For Automatic Assembly-

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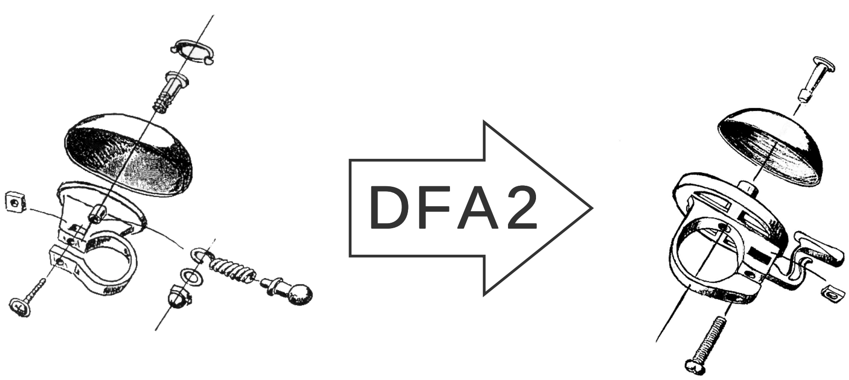

STEPHAN ESKILANDER

DOCTORAL THESIS

STOCKHOLM 2001

DIVISION OF ASSEMBLY SYSTEMS
DEPT. OF PRODUCTION ENGINEERING
ROYAL INSTITUTE OF TECHNOLOGY

DESIGN FOR AUTOMATIC ASSEMBLY-

A Method For Product Design: DFA2

A Doctoral Thesis

by

Stephan Eskilander

Woxéncentrum

a NUTEK competence centre for efficient and easily changeable production

TRITA-IIP-01-02

ISSN 1650-1888

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Stockholm 2001, KTH Högskoletryckeriet

Abstract

This thesis presents a method that supports product developers and design teams to design products for automatic assembly. Product development nowadays is often carried out in parallel to, for example, shorten the development time. Working with product development in parallel implies a need for support methods that focus activities throughout the product life cycle. By focusing the assembly process in product development there is a potential for developing more assembly friendly products. To develop a product that is possible to assemble automatically implies e.g. reduced number of parts, preferably only one assembly direction and parts that are easy to feed.

Techniques known as Design For Assembly, DFA, have been used since the early eighties. Most DFA methods are focused on product evaluation. There is, naturally, a need to evaluate products, but few DFA methods provide the user with information on how to design the product to avoid assembly problems. The method presented, DFA2, is based on a collection of design rules, to provide information to the users on how to design the product. The design rules are aimed at automatic assembly, DFAA, Design For Automatic Assembly (A product designed for automatic assembly will also be easy to assemble manually.) The design rules are sequenced, starting with information regarding the whole object and continue with information for each part in the product. The structure of DFA2 is a way to provide the user with right information at the right time and makes sure that no information is overlooked. Combined with the design rules, DFA2 includes qualitative evaluation criteria since this type of evaluation also tells how to do instead, not only how good or bad the design is.

A method that consists of design rules and qualitative evaluation is ideal to use in the early product development stages. DFA2 also provides the users with a ”common language” that simplifies parallel product development in teamwork between designers, production engineers, quality engineers, purchasers, logistics specialists and so on. DFA2 supports product developers to focus their attention on avoiding one potential assembly problem at the time, in a structured way.

Furthermore, DFA2 supports cost analysis to reveal the costs connected with the design concepts. The cost analysis is based on an activity analysis, which also brings product design closer to assembly system design.

Contents

Earlier publications

Focus on DFA:

Eskilander, S., Byron Carlsson, T., ”Monteringsvänlig produktutformning – förstudie för utveckling av ett ingenjörsverktyg”, Woxénrapport 18, ISSN 1402-0718, 1998 (In Swedish)

Byron Carlsson, T., Erixon G., Eskilander, S., Johansson, R., Peterson, P., ”A flowchart method for design for automatic assembly”, The 1998 international forum on DFMA, 1998

Byron Carlsson, T., Eskilander, S., Johansson, R., Peterson, P., ”A structured set of concrete design rules for design for automatic assembly” Proceedings of the 31st ISATA conference, 1998

Eskilander, S., “Design for automatic assembly – development of a rule based method”, Licentiate thesis, ISSN 1104-2141, 1999

Eskilander, S., “DFA2 – En metod för att utveckla monteringsvänliga produkter”, Woxénrapport 27, ISSN 1402-0718, 2000 (In Swedish)

Eskilander, S., Gröndahl, P., Bergdahl, A., ”A rule based design method for automatic assembly – description and industrial application”, The 2000 international forum on DFMA, 2000

Eskilander, S., “DFA2- ett verktyg för enkel montering”, Verkstäderna, No 8, 2000 (In Swedish)

Eskilander, S., ”Mass production of fuel cells – requirements and preconditions for the assembly process”, IVF-rapport 00012, 2000

Eskilander, S., ”DFA2 – En metod för monteringsvänlig produktutveckling och kostnadsanalys”, Woxénrapport 33, ISSN 1650-1888, 2001 (In Swedish)

OTHER:

Eskilander, S., Langbeck, B., Onori, M., ”Industrial applications of a new FAA machine”, 1st IFAC workshop on intelligent assembly and disassembly”, IAD, 1998

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Broman, M., Eskilander, S., Säfsten, K., ”Interaction between assembly system suppliers and their customers”, Proceedings of the 33rd international seminar on manufacturing systems, CIRP, 2000

Broman, M., Eskilander, S., ”A tool for assembly system design”, Delft workshop on assembly automation, 2000

Awards:

Scholarship in Production Engineering Research from Alde Nilsson ABB Foundation, for the work with DFA2, October 2000

Acknowledgements

The research in this thesis is not the result of a one-man job. During the years many colleagues and friends have offered help and inspiration for me to complete this thesis. I would like to give to...

...My supervisor Prof. Anders Arnström for his never ending enthusiasm, good advises and visionary views...

...Peter Gröndahl for good advices, rivers of enthusiasm and a red pen that never misses anything in order to train us PhD-students in crystal clear thinking...

...Tobias Byron Carlsson, Roger Johansson and Per Petersson, for the excellent teamwork that later became this thesis...

... Roger Stake, Mauro Onori, Marcel Tichem (Delft University), and Magnus Wiktorsson for early comments on my thesis and to Kurt Rapp for very fruitful discussions...

...Colleagues and friends at the Assembly System Division and all the others at IVF(Industrial Research and Development corporation)-KTH(Royal Institute of Technology)-Woxéncentrum...

...All representatives from the companies participating in the DFAA project, for excellent collaboration, enthusiastic discussions and a lot of humour...

…Arnold Johansson, for programming the first software demonstration version of the DFA2 method…

...My fiancée Merete for always being there and encouraging me even though working with this thesis has taken many weekends, evenings and nights away from us...

...My family for encouragement and helping me to keep things in perspective...

...a big, warm hug and from the bottom of my heart: thank you all!

This work consists of results from a couple of projects and has financially been supported by Woxéncentrum, NUTEK (Swedish National Board for Industrial and Technical Development) and IVF. Moreover, the scholarship from Alde Nilsson ABB Foundation has supported the writing of this thesis. The support is gratefully acknowledged.

Stockholm, March 2001 Stephan Eskilander

Structure and overview of this thesis

This thesis consists of four parts:

- Part 1: The research problem, research aspects Chapter 1, 4
- Part 2: Frame of reference Chapter 2, 3
- Part 3: Proposed solution Chapter 5, 6
- Part 4: Discussion and critical review of the work Chapter 7, 8

Part 1 introduces the research problem. This part introduces the reader to the research area and is therefore rather general to its nature. Here, the research method used to approach the research problem is outlined. Part 1 consists of chapter 1 and 4. The reason for separating the two chapters is that the frame of reference pinpoints the research question more than what is made in chapter 1.

Part 2 presents what other researchers have done within this area. Related work is used to position the research in this thesis since a lot of research effort has been put in related areas. Material from this part is then used to build the foundation for the proposed method in part 3.

Part 3 explains the approach for the proposed method as well as describes the requirements on the method. Chapter 6 includes a section of frame of reference. The proposed method is compared to the requirements as well as verifying the usefulness of the method. The method is detailed in appendix.

Part 4 discusses the solution described in part 3 and critically reviews the results. Further research is finally suggested.

This thesis is based on the earlier thesis for licentiate of engineering (Eskilander, 1999). Much of the material in this thesis is similar to the previous thesis. Basically, part 3 has been further elaborated and developed to describe the complete method as well as the verification from using the method in case studies, Fig 1.

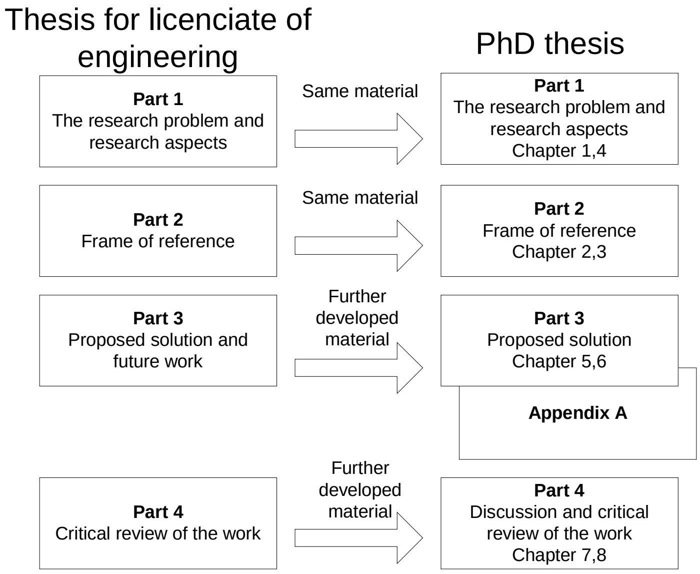

Fig 1: This thesis is based on an earlier thesis

Confidential information

The tests (case stidies) of the method referred to in this thesis are not explicitly described since a lot of confidential information would be revealed. Since the method was tested on products that in some cases are not yet introduced on the market (in March 2001), confidentiality prohibits any detailed information to be revealed in this thesis. Only general results may be discussed. The tests were conducted on these preconditions.

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1 What is the problem?

1.1 Increasing competition

”The world market has probably never been more competitive than today”. This is a saying that is always going to be stated as long as we do not apply any economic system or any ”-ism” that eliminates competition. It was true 20 years ago and is true today and will be true tomorrow. This means that companies must survive on a competitive market by satisfying customer needs.

Technical improvements may create new business areas and any company being able to present a new technical solution may, for a limited amount of time, be alone in that market segment. As time passes, rival companies will probably develop and offer customers similar products, if the product is something the customers want. Being first in a market segment means setting the price levels and standards for how the product can be used. When a rival company offers a similar product there are several possibilities for trying to keep the market share. One may compete with technical excellence, design, image, low price or whatever strategy the company sets. Regardless of strategy, product development is one of the most important activities in order to create competitive products. The success of a product is dictated by its costs, performance and reliability, which to a very large extent are predetermined by the work of the designers.

To stay competitive, companies must have a flexible and agile manufacturing[1] capability. Manufacturing can be a competitive advantage for companies, but that calls for awareness of the manufacturing process within the company. As competition keeps increasing, lead times are shrinking and manufacturing processes are becoming more elaborate. Companies can no longer afford a haphazard approach to design and manufacturing (Pennino and Potetchin, 1993).

[1] This thesis uses the definition of ”manufacturing” as a subset of ”production”. Production is defined as activities and operations such as product design, materials selection, planning, manufacturing, quality assurance and management of the products. Manufacturing is defined as the act or process of actually physically making a product from its material constituents. Hence, manufacturing is a subset of production, and assembly is a subset of manufacturing.

1.2 Product development

Many companies are leaving the traditional sequential product development in favour of the new era of concurrent engineering, as a way of shortening the product development lead-time, as described in, for example, Erixon (1998). Concurrent engineering is basically realising that serial design activities may result in serial (serious) mistakes. According to Meeker and Rousmanière (1996), drastic reductions in development time and reduced number of redesigns may be realised by considering, from the beginning, as much as possible from the entire team. The basic approach in concurrent engineering is working in teams and working in parallel, Fig 2. With this approach, most of the product`s life cycle must be considered in every phase of the product development. One of the more effective ways to achieve this is to work with multi-disciplinary project teams. These teams consist of people from different departments of the company, and the team works together from the beginning of the product development project (Herbertsson, 1999).

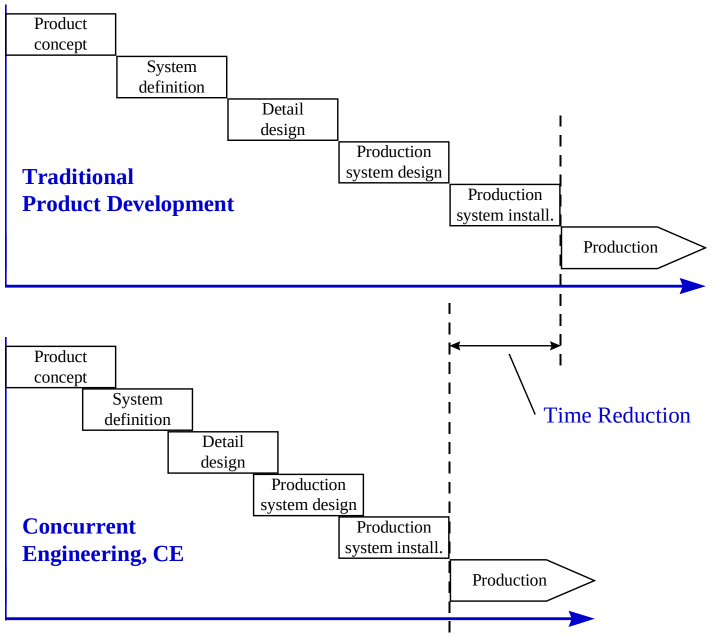


Fig 2: Traditional product development compared to Concurrent Engineering (Erixon, 1998).

By working together in teams, and sometimes in parallel, two major benefits are achieved according to Herbertsson (1999):

1 Early identification and possibility to avoid problems that normally would have been discovered much later in the development chain. The late discoveries of problems regarding manufacturability often results in precipitated solutions and compromises (Miles and Swift, 1992). Since production and manufacturing engineers are involved in the project, it is also possible to avoid potential manufacturing problems.
2 Development time is much shorter compared to the traditional development project. Since much of the work is performed in parallel the total lead-time is shorter, as described in Fig 2. For example, the development of the assembly system may begin before the detailed design of the product is finalised, Fig 3. This way of working also helps to detect and avoid potential problems that would otherwise have been visible much later.

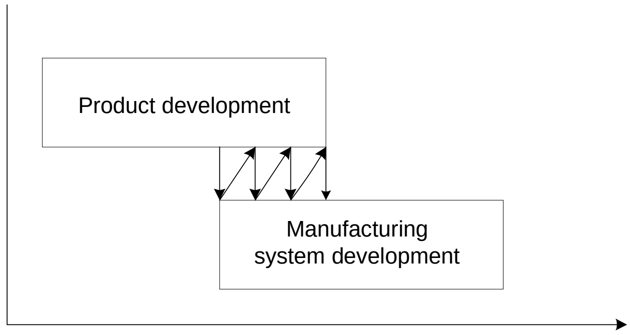


Fig 3: Early, preliminary inputs from product development are needed in concurrent engineering of product and manufacturing system (Wiktorsson, 1998).

Working in parallel, as described in Fig 3, requires early information to be exchanged between, for example, product development and manufacturing system development. This also means that feedback from the manufacturing system development has to be included in the development of the product and hopefully the result will be a better product as well as a better manufacturing system. There is a need for techniques that are capable of visualising the relationships between design parameters and manufacturing parameters (Ahm and Fabricius, 1990).

There is an interesting hen-and-egg problem when designing products and manufacturing systems. The manufacturing process cannot be well defined until the product is designed, but the product cannot be well designed until the process is defined. Manufacturing costs are minimised when engineers from both design and manufacturing are coordinated (Boothroyd and Dewhurst, 1984a). Ideally, the manufacturing costs should be analysed already during the product design phase. To fully realise the benefits of concurrent engineering, an approach to unify a product's design with development of its assembly process is needed (Lee and Hahn, 1996).

1.2.1 Assembly aspects in product development

When developing products, a number of decisions are made that affect the entire company. The product must fulfil certain functional specifications to interest customers to buy the product. The product must also fulfil certain specifications to be able to fit the manufacturing process within the company. This may include specifications for arranging the whole product portfolio, as well as specifications for each part in the products to fit a certain machine or assembly process.

There are techniques for focusing the assembly aspects in the design phase even though the assembly of a product is the last of the production processes before the product is shipped away to a customer. Techniques called ”Design for Manufacturing”, DFM, and ”Design for Assembly”, DFA, are often used to avoid well-known manufacturing and assembly problems. The basic idea is very simple; make sure that the source of problems that are likely to occur in manufacturing and assembly is eliminated even before the product is finished. It is not economically justified in the long run to make the same mistakes repeatedly, only to discover them later in the development process. It is often expensive to make late changes. A survey in printed circuit board (PCB) assembly industry revealed that engineers claimed that more than 70 % of the manufacturing problems are problems that have happened before (Barton *et al*, 1996).

Products designed for manufacturing offer tremendous potential for cost reductions both by simplifying the product, and the related manufacturing system (Ahm and Fabricius, 1990). The special focus on design for assembly can be explained by the fact that assembly is a highly cost-intensive process, which in many cases is impossible to automate without input from the assembly domain (Ahm and Fabricius, 1990). Datsko (1978) foresaw back in 1978 that: ”*Because of open competition the product designer of the future, as he creates and details the design, will knowingly select the processes by which the parts will be manufactured.*” Are we in the future according to Datsko yet?

Manufacturing engineers have already recognised the benefits of techniques like DFA, because they have spent many hours resolving difficult assembly problems after the design has been approved for manufacturing (Scarr, 1986). The foundation for success is created already during the determination of the concept and structure of the product and production system (Olesen, 1991). The product development department has potential for increasing productivity, by means of DFM and DFA, that is significantly higher than the potential manufacturing department has in means of automation (Fabricius, 1994).

Herbertsson (1999) argues that DFA is actually a result of assembly automation. Since the 1950´s, increasing interest in assembly automation started to spread knowledge about design for automatic assembly. Since design of a product aimed at automatic assembly is more difficult than manual assembly, the need for support methods like Design For Automatic Assembly, DFAA, is high.

1.2.2 Automatic assembly aspects in future product development

Depending on the assembly process, the product development team must design the product to fit the specifications of a given process. A human assembly worker is much more flexible than mechanical assembly equipment and therefore the demands for designing the product for manual assembly are usually lower than for automatic assembly. The demands for designing products for automatic assembly have not got the highest priority within product development as the most common assembly process is manual assembly. Moreover, the human assembly worker is a masterpiece of versatility and sensing capabilities and can perform many assembly operations that no machine can duplicate economically (Swift and Redford, 1978). However, each human assembly worker is limited by its capacity not to work more than a few hours per day. To increase output from the assembly shop, management can employ more assembly workers or buy more automatic equipment.

Having a productive and flexible manufacturing process is probably going to be a requirement for staying competitive. In some cases, automation can be the answer to increasing productivity. Hsu *et al*. (1998) expressed this possibility: ”*Increasing productivity through automation is one avenue of achieving competitiveness*”.

An assembly system can be partly manual and partly automatic. When products are modularised, each module can be assigned to an assembly system. This would follow the way pointed out by Erixon *et al* (1994) and Erixon (1998), that products within the product gives the possibility to arrange the manufacturing system as factories within the factory, see Fig 4.

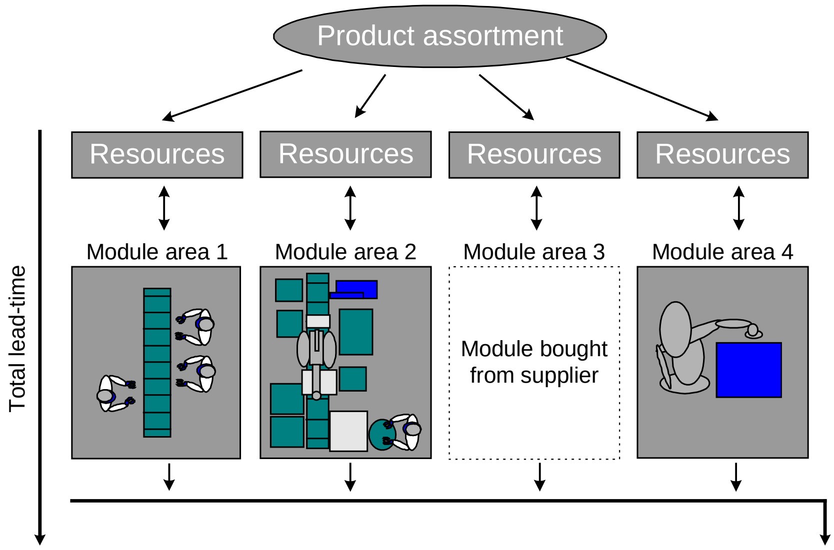


Fig 4: A modular product gives the possibility of designing a modular assembly system (Erixon et al, 1994).

Arranging an assembly system like in Fig 4 gives the possibility to automate sections of the product assortment. Suppose that module area 2 in Fig 4 assembles a module that is used in several products throughout the whole product assortment. Then it might be economically feasible to use for example a flexible automatic assembly system, since it must be able to handle several variants of modules and thereby, the costs of the assembly systems can be shared between many module variants.

The technology for applying flexible automatic assembly is already available if not fully exploited. For example, the MARK III system could assemble about 120 different variants of electric connectors with no changeover time between variants (Langbeck, 1998). Other studies show that the MARK III system was capable of assembling a wide range of different products, thus it may be called a standard assembly system (Eskilander *et al*, 1998).

With an automatic assembly system in the factory, the products need to be designed to fit this assembly process. Products must be designed for automatic assembly if maximum utilisation of emerging technology is to be obtained (Bailey, 1983). It is becoming more important to ensure that product design is compatible with automated assembly techniques (Hernani, 1987). Techniques like DFAA are necessary in order to use the automatic assembly process better and economically justify more automatic assembly and make systems like the MARK III system more common in industry.

1.3 Initial problem description

There is a need for a supporting method for product design that focuses automatic assembly. But how should such a method be structured and used? Norell (1992) concludes that a support method must:

1 Be easy to learn, understand and use.
2 Contain accepted, non-trivial knowledge within the area it is used.
3 Support the users to find the weak areas in the product.
4 Be a common platform to create a common language for several different professions.
5 Support teamwork and to continually educate and support the users.
6 Contribute to a structured way of working.
7 Provide measurable effects from the development work.

The requirements above are fundamental requirements for any method aimed at product development. However, the focus on automatic assembly makes for example requirement 4, described above, more important than it first appears. The special conditions for automatic assembly are not always common knowledge among product developers. Further, requirement 2 and 3 suggests that a method that focuses automatic assembly must contain special knowledge about the automatic assembly process and must pinpoint what features in the product that do not fulfil the requirements (both technical and economical). What kind of supporting method aimed at automatic assembly can fulfil these requirements?

Hence, the initial research question in this thesis is;
How can a method that supports the development of products designed for automatic assembly be structured and used?

2 What is Design For Assembly, DFA?

2.1 Background for DFA

The struggle to make products easier to manufacture and assemble has probably been considered as basic engineering skills since industrialisation began. Statements like ”But this is how good engineers work anyway” are common when DFA is introduced, but as D´Cruz (1992) replied to an engineer at the Rover Group: ”*From the evidence of the designs that are produced at present, maybe we sometimes need a little help*”.

There is no absolute definition of “Design for Manufacture”. It can be defined in various ways, from a relatively narrow ”product design for producibility” to the broader ”*design* of product and process specification *for* cost effective, reliable *manufacture* to achieve customer satisfaction and business success” (Miles, 1989). DFM concepts helps designers change from ”doing the right thing” to ”doing things right” (Fabricius, 1994).

Herbertsson (1999) argues that there are examples of product simplifications similar to the Design For Manufacturing concept, as early as from Henry Ford in the 1920´s. During the period between 1940´s and 1970´s many manufacturing companies experienced extreme growth. They were mass-producing products in few variants with focus on exterior design and functional issues rather than on manufacturing properties of the products. The design departments had no great pressure on focusing DFM since the economy of scale advantages were considered to minimise manufacturing costs (Herbertsson, 1999).

Increased labour costs forced companies during the 1960´s to focus more on automatic assembly. As a consequence, in the 1960´s and 1970´s knowledge about the relations between product design features and automatic assembly processes increased (Herbertsson, 1999). Cross (1993) claims that the very first conference on design methods was held in London 1962. The first real DFA methods appeared in the early 1980´s according to Herbertsson (1999) and more recently Egan (1997) reports of twelve commercially available DFA methods.

There are several techniques or supporting methods to help product developers improve their work. In Fig 5 Miles (1990) gives an overview to the relationships between some tools and techniques and their impact on quality, cost and delivery of the resulting product.

Measurements and improvement techniques

● STRONG
○ MEDIUM

Improvement		QFD	Design For Assembly	Concept evaluation	FMEA	Design quality improvement	Design to cost	Reliability techniques	Manufacturing simulation
Quality	Robust design	○	○	○	○	●		●	
	Customer satisfaction	●		○	●	●		●	
	Right first time designs	●	○	●	●	○		○	●
Cost	Lowest cost manufacturing		●	○		○	○		○
	Lowest investment cost		●	○			○		●
	Achieve target cost		○	○			●		○
Delivery	Minimum lead time	○	○		○				○
	Deliver on time					○			○

Fig 5: Techniques versus performance improvements (Miles, 1990).

Note the circle under ”Design For Assembly” and ”Right first time designs” in Fig 5. This thesis may be reason for Miles to make it a filled circle next time.

2.2 DFX and other acronyms, what is the difference?

Being a designer is difficult. You have to consider demands from all parts of the company, customer demands and laws from authorities while trying to make a profitable product. During the whole lifecycle of a product there are requirements on the design that must be considered during the design phase, Fig 6.

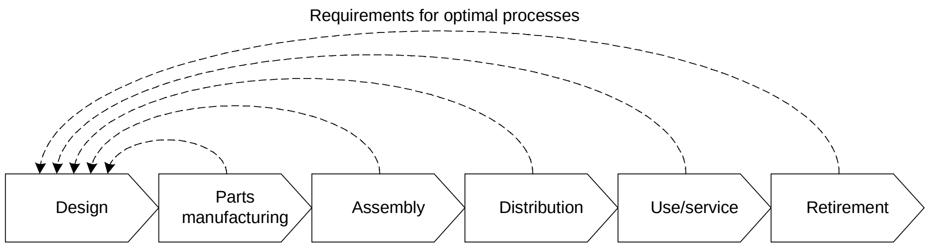


Fig 6: Demands on the design from all parts of the product lifecycle (WDK, 1993).

Since Design For Manufacturing, DFM, and Design For Assembly, DFA, were introduced, there is now an acronym for almost any activity or focus for designers. DFM is sometimes referred to as Design For Manufacturing and Assembly, DFMA (Egan, 1997), Fig 7. However, the term DFMA is also a trademark for one of the commercial DFA methods available.

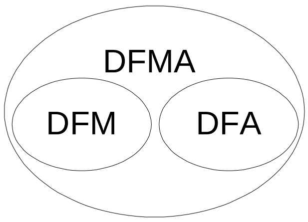


Fig 7: DFMA consists of DFM and DFA (Egan, 1997).

The jungle of acronyms starting with ”Design For...” is often simplified by using the acronym DFX, Design For X. DFX can be regarded as a goal focused activity with the purpose to fit the product to the life phase system (Erixon, 1998). There are many different interpretations of the X. WDK (1993) has two interpretations of the X:

1 A lifecycle phase of the product (e.g. parts manufacturing, assembly or service) or one of the sub processes (e.g. gripping or feeding).
2 A specific property (e.g. cost, quality or environmental effects).

Taken into account the whole lifecycle of the product, its properties involve its function as well as its manufacture and possibilities of reuse (Meerkamm, 1994). These different aspects on DFX can be visualised in a matrix, Fig 8:

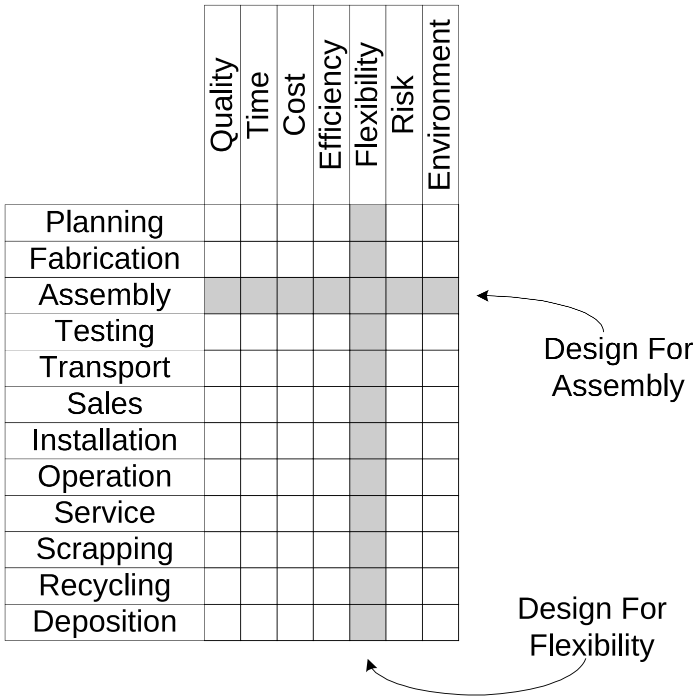


Fig 8: DFX as lifecycle oriented or ability oriented (WDK, 1993).

According to Stoll (1986) the greatest single opportunity for product design improvement using the concept of DFM has been in the area of assembly, DFA. This can depend upon the fact that it is in the assembly workshop that the parts for the first time comes together as a whole product, and therefore it is visible how all parts must interact. Another explanation can be that most other DFX methods besides DFM and DFA are rather young and have not become frequently used yet.

DFA rests on the hypothesis that through improvements in assemblability of a product, improvements in other processes will follow automatically (Erixon, 1998). Since the product is simplified through the use of DFM or DFA, it will affect the entire production process and production staffing (Ahm and Fabricius, 1990). This will also lead to less need for manufacturing equipment and space, while at the same time opportunities for automation etc. will increase (Ahm and Fabricius, 1990).

While concurrent engineering becomes more and more applied in industry, the job of a designer is not becoming easier. One way of making sure that more departments of the company can give direct input to the design work is to work in multifunctional teams. To these teams, the use of a DFX tool is a way to focus their attention and to provide a common language.

2.2.1 What is the difference between DFA and DFAA?

This thesis is focused on developing a DFAA method. DFAA, Design For Automatic Assembly, is based on the same approach as DFA, but with the exception that DFAA has a clear focus on automatic assembly. Hence, DFAA can be regarded as a subdivision to DFA, see Fig 9.

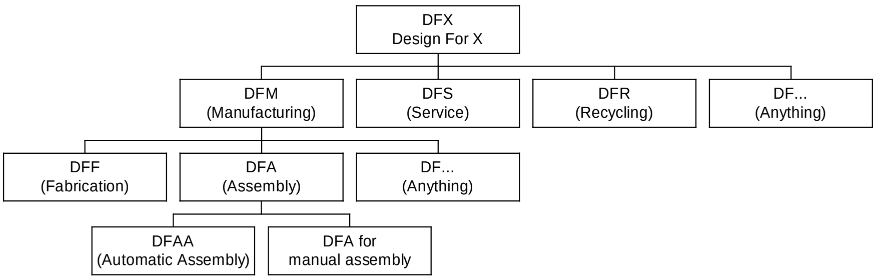


Fig 9: DFAA as a part of DFA, based on life cycle properties.

DFA in general may address the problem of manual or automatic assembly, while DFAA is focused only on automatic assembly. Many authors discuss ”robotic assembly”, for example Bailey (1983), Scarr *et al* (1986 IEEE), Rampersad (1994) and Boothroyd and Dewhurst (1984b). Robotic assembly is here included in automatic assembly. Any mechanical assembly process is in this thesis named automatic if it can perform assembly operations without human interaction. The problems are very much alike regardless if the assembly process is hard automated or flexible automated.

2.2.2 Why focus on DFAA?

Many of the DFA methods available today are focused on manual assembly. There are several aspects that are different in comparison between manual and automatic assembly. For example, the human being is very flexible in movement, speed, force, vision and in the ability to feel if an operation is correct and perhaps change it. These aspects are not as simple for a mechanical assembly unit or a robot. Therefore, there is a need to simplify the product in order to enable assembly with mechanical units. These simplifications may seem evident and just common sense, but still, when taken all into consideration, it is important to remember these many aspects. With a good producibility design, automation projects can be successful (Miyakawa, 1990a). A successful product design project includes low manufacturing system costs, which preferably are analysed early in the product design stage.

Maczka (1985) states that *”Trying to automate an assembly operation without defining, evaluating and possibly redesigning the product is like trying to improve a parachute release system without checking the condition of the parachute; the attempt was a good idea, but will probably fail in the end”*.

Scarr *et al* (1986) also concludes that products need to be designed for automatic assembly to fit an automatic assembly process: *”Many of the problems presently being encountered in automated manufacture stem from the fact that the products which are now being produced were originally designed for conventional manufacturing and assembly”*.

If a product is prepared for automatic assembly, it will also be much easier for a human to assemble. Maczka (1985) agrees: *”Any product designed for automated assembly will be easier to assemble manually”*. However, working with DFA for manual assembly does generally not make products suitable for automatic assembly. Bailey (1983) states that having a product designed for automatic assembly allows maximum flexibility in the actual assembly process, since the product can be assembled manually or automatically. Designing a product for automatic assembly will also result in great increase in both productivity and product quality, even if automation is not used according to Maczka (1985). Herbertsson (1999) notes that in the 1960s, when products began to be redesigned for automatic assembly, it was often discovered that the redesigned product was so easy to assemble manually that automatic assembly was no longer economically feasible. So, a company that wants to start working with DFA should aim for DFAA from the start, since it offers more potential benefits than DFA for manual assembly.

2.3 Effects of DFA

Working with DFA has potential benefits that are well documented along a wide range of products, (Egan, 1997). Even though the focus is on assembly, assembly driven methods have proven to be very powerful DFM tools (Erixon, 1998). For example, General Electric has identified DFM as a way to reach world class in product and process design (Deisenroth *et al*, 1992).

According to Fabricius (1994), manufacturing costs can typically be reduced with about 30 per cent without compromising on the product quality. Edwards (1997), Boothroyd (1994) and Ahm and Fabricius (1990), just to mention a few, reports of several companies that have reduced costs as a result of working with DFA. Egan (1997) classifies potential benefits into two categories:

- Short term. Initial goals for implementing DFA are often cost based, typically:
    - Reduced number of components
    - Reduced assembly time
    - Reduced manufacturing and assembly costs
- Long term. When applying DFA on more than one product there are potential long term goals for the whole company, such as:
    - Improved product quality
    - An environment for concurrent engineering

2.3.1 Short term effects

The short-term benefits are often easy to accomplish. Almost any product has the potential of reducing the number of parts. Any part that is excluded from a product means no change orders, no documentation, no purchasing, no storing, no handling, no assembly, no testing, no service, no recycling and so on. Working with DFA helps the product development team to focus on part reduction in a way that is very effective. With fewer parts, the assembly time will most probably be reduced (as well as less work for all the departments in the company that no longer deals with this part) and the company will experience a shorter lead-time. Fewer parts to assemble and shorter assembly time will also contribute to lower manufacturing and assembly costs and higher quality. Petersson (1998) argues that the ease of assembly in a product influences the required plant size, since fewer parts and simpler assembly systems for example need less space.

Fig 10 illustrates how part reduction may be achieved. The redesigned bicycle bell is not an ideal product since the fastener of the bell onto the bicycle is not the best. However, it is an evident example of how assembly may be simplified with the use of DFA. Part count is reduced from ten to three.

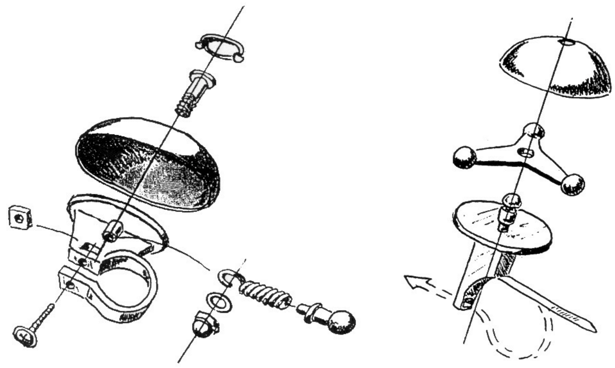


Fig 10: Example of how a bicycle bell could be redesigned.

The general benefits from working with DFA may be summarised as in Fig 11.

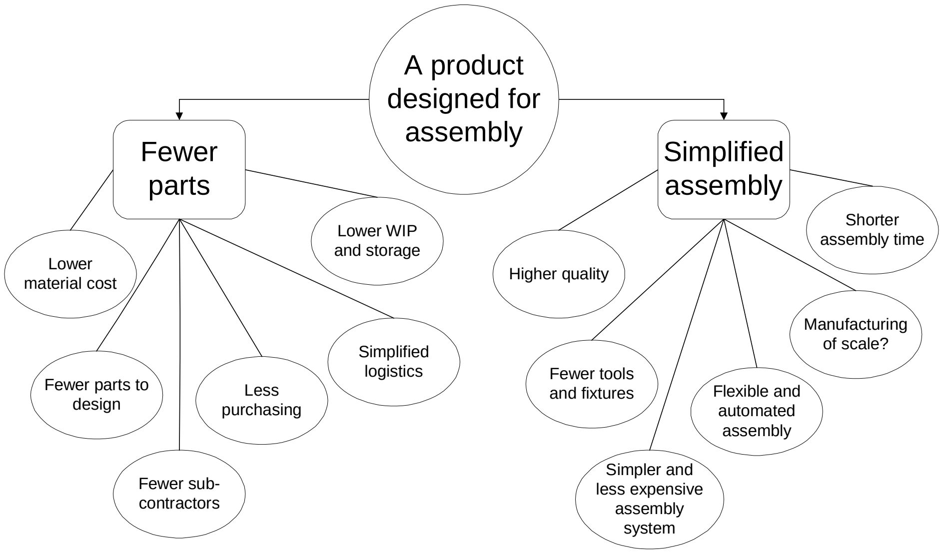


Fig 11: Examples of potential effects when DFA is used in product development.

Unfortunately there is no way of quantifying the benefits of working with DFA on beforehand. Naturally, some companies are better on including the requirements from the assembly process during product development. Hence, different companies will reach different levels of benefits when starting to work with DFA.

2.3.2 Long term effects

The long-term benefits are not as easy to accomplish. In order to really improve product quality one has to focus DFA on all products being developed and preferably also on existing products that are redesigned. Soon, the DFA thinking will be a self-spoken way of thinking in every project since it helps to avoid potential quality problems and assembly difficulties. In concurrent engineering there is not even a possibility to work in sequential order in product development. Therefore, DFA is a way of bringing up assembly aspects early in the product development project. DFA methods have forced product designers to accept their role in eliminating assembly complexity and are increasingly used because of their success in product development efforts (Lee and Hahn, 1996). D´Cruz (1992) reports that DFA acted as a focus for the product development team and helped promote teamwork in case studies at the Rover group.

When working with DFM and DFA, besides all cost reductions, experience also shows a reduction in overall product development time, which enables manufacturers to launch their products faster on the market (Ahm, Fabricius, 1990).

2.4 Benchmarking with DFA

A DFA analysis can be performed to highlight strengths and weaknesses on competitor products. A DFA analysis does not replace the essential qualities of design engineers such as innovation, talent or experience, but instead strengthens them and stresses the need for creativity, (Freckleton *et al*, 1993). Using a DFA analysis as a benchmarking tool can help companies to compare their products to their competitors products, and thereby find ways of closing eventual gaps between the products (Freckleton *et al*, 1993). Miles (1989) notes ”*Evaluation results can be used to compare alternative design solutions or indeed to evaluate competitors products”*. Since alternative design solutions can affect assembly, fabrication, purchasing, inventory and other overhead cost categories in conflicting ways, the comparison can many times be very valuable (Funk, 1989).

Competitors’ hardware is a rich source of information providing concepts and design solutions, current market trends, cost and quality drivers and missing or unwanted functionality according to Meeker and Rousmanière (1996). Branan (1991) reports that Motorola used DFA as means for a benchmarking study with competitors' products. After redesigning the Motorola product from the ideas that were found in competitor products, assembly time was reduced by 87 % and assembly defects were reduced by over 80 %. Unfortunately, many companies still suffers from the ”not invented here” syndrome and refuse to use this rich source of information (Meeker, Rousmanière, 1996).

2.5 How to implement DFM or DFA

There is probably no ”right way” for all companies to start implementing DFA or DFM. Miles (1990) suggests that the initial use of DFM must be ”opportunity driven”. This means finding the right product at the right time, using the right tools or techniques, and being addressed by the right team. Finding this first successful demonstrator can then help identify further opportunities to be pursued until simultaneous engineering and DFM or DFA tools and techniques become a normal process for new product introduction. An implementation strategy suggested by Miles (1990) is:

- Provide awareness at business unit executive level aimed at
  — confirming that DFM methods could benefit the business
  — obtaining executive commitment for a pilot project
  — identifying a carefully selected product opportunity for a pilot project that will provide benefit to the business
  — agreeing objectives for the project and selecting the tools and techniques to be used
- Undertake team-based pilot project to improve the design of a specific product and demonstrate that the DFM team-based approach works with their products, their employees and their technology. This is usually done in a project team workshop with a DFM facilitator to arrange training sessions and to help keep the discussions ”on track”.
- Pursue specific product development proposals that are identifying other opportunities for ”techniques supported” team based activities.
- Change the product introduction process and its organisation to reflect the need for multi-functional teams using tools and techniques when dealing with major product design or redesign opportunities.
- Introduce appropriate measures of performance and project management to provide executive control over product design activities in terms of quality, cost and delivery.

Dean and Susman (1989) describes four different approaches for organising the company for ”manufacturable design”:

1 Manufacturing sign-off. This means that manufacturing engineers are given veto power over product designers meaning that a design cannot be released without manufacturing's approval. The major drawback is, of course, the unbalance between departments since manufacturing is equipped with a lot of power and no grounds for creative interchange between the two functions is there. However, manufacturing sign-off is relatively simple to manage and depends little on interpersonal skills of engineers in either department.
2 The integrator. Integrators working with designers on producibility issues, serves as liaisons to the manufacturing group. Naturally, this approach requires the integrators to keep both design and manufacturing perspective in balance. If the integrator leans too much to either side, he or she will loose credibility at the other department or simply not get the job done. The education system where manufacturing and design engineers have separate educational programs makes it hard to find engineers that are educated and promoted as integrator candidates. The approach is reasonably flexible since a single individual or a small group can easily keep track of new capabilities in manufacturing. The disadvantages are the so called ”guru syndrome”, since integrators are there to worry about producibility, no one else does. Further, the organisation becomes very dependent on one, or a few, individuals and the approach does not promote concurrent engineering.
3 Cross-functional teams. Cross-functional teams mean collaboration from the start. At the very minimum, a cross-functional team consists of a design engineer and a manufacturing engineer, who work together throughout the whole product development process. The team meets regularly and are preferable located in the same room. This approach facilitates concurrent engineering and the manufacturing engineers become familiar with the design well before it is released and can also influence the design of the product. No approach is without friction, and this approach can be met with design engineers feeling that quality assurance and manufacturing are pre-empting them, and wondering why the company do not trust them to create good designs independently. Designers can feel upset that this new system undermines their creativity and that manufacturing's demands are often unrealistic, especially concerning wide clearance tolerances. Some of the benefits are that manufacturing can more or less have a finished manufacturing system finished at the same time as the product is finished. The approach requires members in the teams to gain broad expertise in producibility, since there is no longer one single expert in that area.
4 The product-process design department. This approach involves the greatest degree of structural change of these four approaches described. It means

creating a single department responsible for both product and process. The one-department approach permits concurrent engineering and inevitably leads to mutual education through day-to-day contact. Further, it places s high premium on the technical and interpersonal skills of department members. There are different variants of this approach:

- A senior manager responsible for both product and process design, but separate sub units for each function.
- A manager having responsibility for a group of both product and process engineers that are combined into a single department.
- One department consisting of product-process engineers, that is, engineers with responsibility for both aspects of design. This is a rarely found ideal, since very few people have the skills necessary to straddle both worlds.

Norell (1992) concludes that to succeed with implementing DFA it is important to appoint one person to have the responsibility for the method. This person has to inform everyone involved in product development, management and anyone else who will come in contact with DFA about the method. The ”DFA manager” also arranges courses in DFA, acts as a supporting department, builds up routines around DFA and follows up experiences from DFA.

Ahm and Fabricius (1990) concludes, ”*It is imperative that the management should be aware of and understand the procedure involved in DFM projects, thus accepting the fact that the early phases of product development are more than usually resource-intensive and that resources are allocated to the production departments for participation in development projects. Experience shows that this additional investment pays for itself several times over during the detailed design phase and product manufacture.”*

2.6 Why is not DFA used more?

Carlsson (1996) reports of three major reasons why Swedish industry is not using DFA more:

- ”*Poor knowledge about the methods*”
  The most obvious reason is that few know about the methods. In a few companies, there is a small specialist group that knows of the methods available, but production engineers and designers have little knowledge about the methods, according to Carlsson (1996).

- ”*Management priorities*”
  Of the companies in the survey conducted by Carlsson (1996), all of them had product performance higher prioritised than low manufacturing costs, and thereby no great pressure from management for lowering this.
- ”*Work overload*”
  Finally, engineers felt that their workload is so high they do not have time to work with another method Carlsson (1996).

Furthermore, designers feel they have not been shown any significant economic proof for starting to work with DFA, and thereby no pressure from management (Carlsson, 1996). The lack of economic proof of why companies should work with DFA is a big problem. There is, yet, no reliable way of estimating how much money a specific company can save if working with DFA. It all depends a lot on how good the products are designed today and how well a DFA method can be implemented. There are a lot of case studies showing significant savings. Boothroyd and Dewhurst (1998) reports of, just to mention a few, the following average reductions in over 100 industrial case studies (the results are used as sales argument and may therefore be considered only as indications):

- 54 % part reduction
- 63 % reduction of product development cycle time
- 42 % reduction in labour cost

However, there is no way of guaranteeing a certain amount of reductions for a new company.

2.7 Possible drawbacks with DFA

There are ways to use DFA and only achieve disappointing results. Ulrich *et al* (1993) discuss mainly two drawbacks: Time and cost. These drawbacks may not meet the expected limits:

- Time.
  - The time to design the product may be longer than expected if DFA activities are included. Especially design teams that are not used to working with DFA may experience a longer design time (hopefully the time for re-designs will be shorter instead).
  - The time to market may be delayed if DFA is used in an unfortunate way. Assume that a certain DFA level is supposed to be reached, then the product may have to be re-designed

more than planned to meet these requirements and time to market may be delayed.

- Cost.
    - Product cost may be increased if parts are integrated resulting in very complex parts. The costs for manufacturing a complex part may be higher than the costs for e.g. four simple parts that require assembly.
    - System costs may also increase if integration of parts results in complex parts that are difficult to manufacture. The manufacturing processes and tools may be complex and expensive, and in worst case quality losses may increase if DFA is used in an unfortunate way.

Most of these potential drawbacks may be avoided if DFA is used not by designers alone, but in design teams including production engineers, quality engineers etc. By including different competences in the design team, the potential drawbacks may be identified early and, hopefully, avoided.

2.8 Implications for this thesis

There is a lot of work done in the area of design for assembly. However, there are still areas that need further development. A method that supports product design should be focused on automatic assembly since it also will be beneficial for manual assembly. A new DFA-method should, besides the already known benefits of part reduction, support product designers in their efforts of designing products that are adjusted to fit a generic automatic assembly process. Regardless of the structure of the method, the result after using the method should be such that it serves as a base for benchmarking.

Any method is going to need support in its implementation phase. The easier it is to show the benefits from the method, the easier it will be to start using it. There are also aspects on the user friendliness that must not be forgotten. The easier it is to learn how to use a method, the less barriers to overcome in implementation phases.

In conclusion, there is a need to develop a method that is very easy to learn and to use to make sure that more people can take the time to use it. Furthermore, it must present a result that can be used to compare different products (both technical and economical aspects) and that can be used as a common language in development teams.

3 Related work

3.1 General design methods

There are design models that try to prescribe the design process in such a way that the probability for designing a well functioning product increases. One such model is presented by Pahl and Beitz (1988). Their model prescribes four main activities in the design process: clarification of the task, conceptual design, embodiment design and detail design, Fig 12.

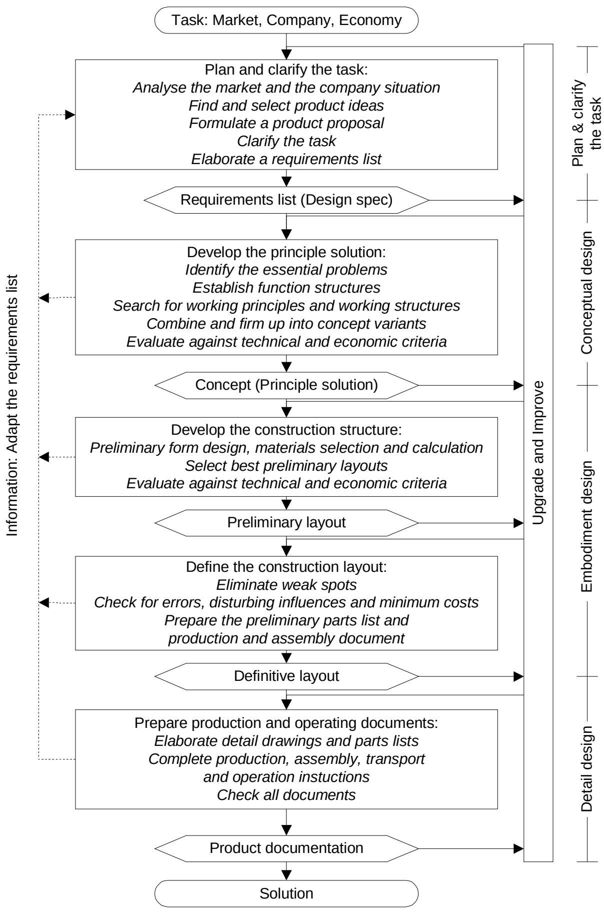


Fig 12: Model of a design process (Pahl and Beitz, 1988).

The model is an example of a top-down like approach, where the work starts with a rough concept and ends in a detailed design. Wiktorsson (1998) notes that similar models are found in Ulrich and Eppinger (1995), Hubka and Eder (1992) and Pugh (1990).

This thesis is focused on methods that can be used in the different stages of the design process, even already in conceptual design. One method that supports the whole process described by Pahl and Beitz (1988) and includes DFA is the Modular Function Deployment (MFD) method by Erixon *et al* (1994) and Erixon (1998) for designing modular products.

As pointed out by Sundgren (1998), the MFD-method for structuring products in modules is the most detailed and most used one.

The method consists of five different steps see Fig 13;

1 Starting with clarifying the customer requirements for the product. This is analysed with the QFD (Quality Function Deployment) tool.
2 Based on the customers' requirements, the next step is to select technical functions. Usually, establishing the functional structure and then choosing technical solutions for each function do this.
3 The heart of the method is the Modular Indication Matrix, MIM. This matrix is a way of identifying possible modules based on the chosen technical solutions.
4 When the modules are chosen from the MIM, the next step is to evaluate the concepts.
5 Finally the modules are documented and improved by using, for example, DFM or DFA.

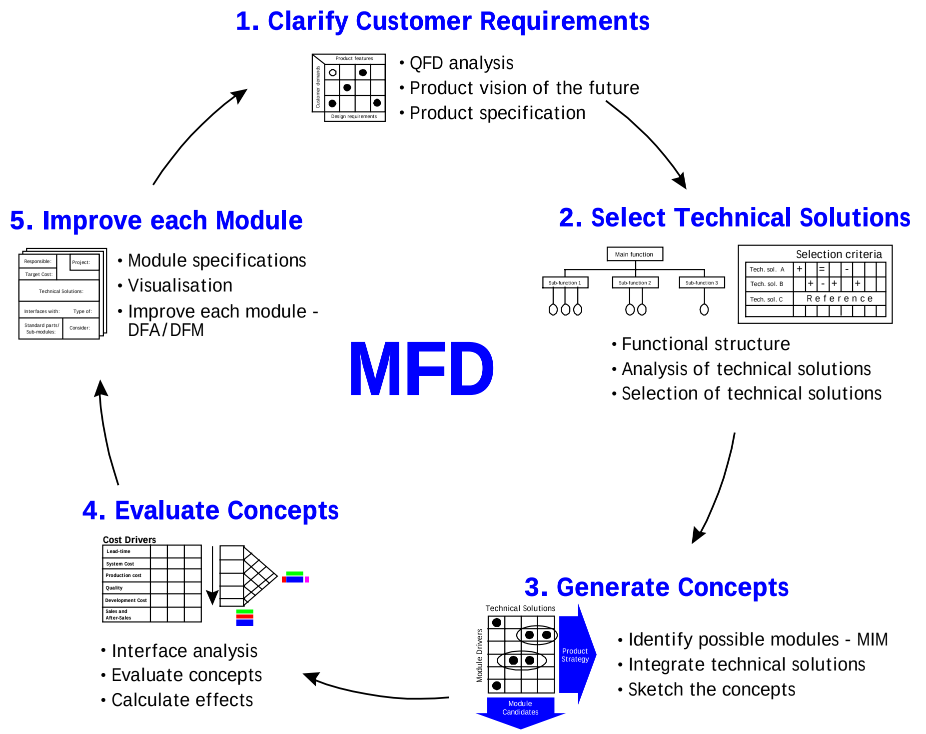


Fig 13: The five steps in the MFD method (Nilsson and Erixon, 1998).

The method suggests the user to do more than one loop, that is, working with the five steps more than once. In step five each module is documented and improved by the use of DFM or DFA. The DFA tools used for this purpose are often focused on evaluating a product, as will be discussed in the following sections.

3.2 Evaluation philosophies in DFA

3.2.1 Two approaches

To improve a phenomenon, an evaluation process is necessary in order to know what and preferably how to improve, as well as to compare the results before and after the improvement. Evaluating a phenomenon involves choosing one or a few parameters that are measurable and then evaluating the phenomenon regarding these parameters.

Customers buying a product typically measure price and functions in order to compare similar products. The evaluation is based on objective measures such as price and performance but also on subjective opinions as whether or not the design is satisfactory or if the brand has the type of image the customer wants. These parameters may be called order qualifiers and order winners (Hill, 1993). An order qualifier for a product qualifies it for the final evaluation where the customer chooses the order winners he or she considers important. An order qualifier can for example be the price of the product, the customer can choose between a couple of products in the same price range that fulfils the basic function. An order winner may, for example, be low fuel consumption for a car that contributes to a good total economy. But since customers have different needs, a parameter that is only an order qualifier for one customer may be an order winner for the next.

Evaluating a product to determine if it is suitable for manufacturing means identifying a number of parameters that are vital for the manufacturing process. The parameters should then be interpreted as demands on the product. For example, a certain manufacturing process has a set of vital process parameters that must be fulfilled in order to produce the required products. Identifying these parameters is important since they are similar to order qualifiers, that is, they ensure that the process may be accomplished. The parameters can be interpreted as process demands for each part of the product. There are also parameters that can simplify the manufacturing process and thereby save time and money, comparable to order winners. These parameters can be interpreted as special demands for designing the product.

Evaluating products to measure how suitable they are for assembly is very much depending on the assembly process. Manual assembly requires certain parameters to be evaluated and automated assembly usually requires even more parameters. The problem is to find the best parameters to measure. Daetz (1987) states, ”*The first step to achieving consistent quality is being able to measure attributes of interest*”. Being able to identify ”attributes of interest” also means knowing the requirements of the assembly process in question. There are some different approaches for evaluating the assemblability of a given product. Component and assembly cost or estimated assembly time are not the only measures of how well a product is suited for manufacturing (Hight *et al*, 1995).

Holbrook and Sackett (1988) points out that in evaluating products with DFA it would be preferable to be given specific advice on how to redesign instead of just be given negative comments about an existing design. This calls for a discussion of qualitative or quantitative evaluation philosophies.

Miyakawa *et al* (1990) notes that ”*Assemblability is an abstract concept, and thus difficult to measure directly”*. A qualitative measure is a criterion that a product preferably should fulfil to fit the assembly process. If the product does not completely fulfil the criterion, there are usually steps to identify how far away from the ”perfect solution” the product is. Hereby, a product may be evaluated compared to an ideal solution, and every attribute that does not fulfil the criterion is then a potential area for improvement. According to Takahashi (1989), the best evaluation is whether a product fits a production method or not. But, as Shimida (1992) points out, it is in the early design stages difficult to quantitatively evaluate whether the product will be easy to produce or not.

In this thesis qualitative evaluation is defined as evaluation criteria that is used to decide whether the product does fit a certain assembly process or not. The evaluating requirements themselves give information about the preferred solution that will fit the assembly process. This information could be valuable if it is used in early product development.

Quantitative evaluation is here defined as evaluating a product and being given the answer that it takes X seconds or X SEK to assemble, not giving specific advice on how well the product fits the assembly process. Quantitative evaluation does not give explicit information about the preferred solution for the assembly process.

3.2.2 DFA methods

There are several design methods available to support product development. Sackett and Holbrook (1988) report in 1988 of nine different research systems for DFA. More recently Egan (1997) reports of twelve commercially available DFA methods:

DFA method	Authors	Country of origin
Assemblability Evaluation Method (AEM)	Ohashi Yano	Japan
Boothroyd-Dewhurst DFMA	Boothroyd Dewhurst	USA
A systematic approach to Design For Assembly	Miles Swift	UK
A designers guide to optimise the assemblability of the product design (DGO)	Hock	USA
ASSEMBLY	DeWinter Machiels	Belgium
Assembly Oriented Product Design (AOPD)	Bässler Warnecke	Germany
Assembly SYStem (ASSYST)	Arpino Groppetti	Italy
Assembly view	Sturges	USA
Design for Assembly Cost-effectiveness	Yamagiwa	Japan
Product and System Design for Robot Assembly	Davisson Redford	UK
Product Design Merit	Zorowski	USA
The DFA House	Rampersad	The Netherlands

Table 1: Commercially available DFA methods (Egan, 1997).

DFA tools give designers insight in assembly issues to anticipate and ease assembly difficulties of a product (De Fazio *et al*, 1997). The DFA methods are all somewhat different. In the following sections the differences between some of the better-known methods are outlined.

This thesis is about creating a new DFAA method. This DFAA method should be a support for <u>how</u> to design each module, as described in step five in the MFD method, not only evaluating how good or bad each module is. What type of evaluation system is needed?

3.3 DFA methods with qualitative evaluation

3.3.1 The SINTEF method

Langmoen and Ramsli (1983) defined flexible automated assembly to include any assembly system that contains at least one robot arm and different easily adjustable feeders. They developed a method to clarify which products that were candidates for flexible automated assembly, called the SINTEF method. The method uses five difficulty levels, Table 2, to evaluate a product for each of 19 criteria, Table 3.

Points	Description
0	Very easy to automate
1	Easy to automate
2	Possible to automate
4	Difficult to automate
8	Best solved manually

Table 2: Difficulty points for evaluating flexible automated assembly (Langmoen, Ramsli, 1983)

Evaluation criteria for each part

Table 3 shows a selection of criterions that are used to evaluate each part of the product and Table 4 show examples of criterions that are used to evaluate the whole product.

Criteria	**Part points**				
Description	**0**	**1**	**2**	**4**	**8**
Delivery	Oriented		In bulk		Single packed
Fragility	Not fragile		Can not fall over 200mm	Can not fall over 50mm	
Quality	P< 0,1%			0,1% ≤P≤ 1,5%	P> 1,5%
Securing	Self securing		Screw, nail, fast gluing	Weld, solder	
Insertion	Linear			Linear + rotation	Coaxing
Combined movement	Two parts			Three parts	Four or more parts
Tolerance	T> 0,5mm		0,1mm <T≤ 0,5mm or note 1	T< 0,1mm or note 2	Note 3

Table 3: Qualitative evaluation criteria and points given to parts in the product according to the SINTEF method, after (Langmoen, Ramsli, 1983).

Note 1: *T> 0,5mm if*
H/D and L/B or H/B >10, where
H= Insertion length, D= Diameter of a hole, L= Longest side of enclosing rectangular, B= Shortest side of a rectangular hole

Note 2: *0,1mm ≤T≤ 0,5mm if*
H/D or L/B >10

Note 3: *T< 0,1mm if*
H/D or L/B >10

Evaluation criteria for the whole product

The criterion continues for the whole product.

Criteria	Product points				
No	**0**	**1**	**2**	**4**	**8**
Weight	0,1g <G≤ 2kg	0,01g <G≤ 0,1g 2kg <G≤ 6kg	G< 0,01g G> 6kg		
Size	5mm <L≤ 0,5m	2mm <L≤ 5mm 0,5m <L≤ 2m	L< 2mm L>2m		
Number of parts	N< 20		20 ≤N≤ 40	N> 40	
Base component	Yes	No			
Assembly directions	1, 2 or 3		4 or 5	6	

Table 4: Qualitative evaluation criteria and points given to the whole product according to the SINTEF method, after (Langmoen, Ramsli, 1983).

If a part gets four or eight points at any of the criteria in Table 3, the SINTEF method suggests that part as a candidate for redesign. Using these qualitative measures to evaluate a product, the result tells the user of the method how difficult it would be to automate the assembly process. The product with the lowest score of points is the one most suitable for automatic assembly when comparing two or more alternative designs.

The SINTEF method is an example of a qualitative evaluation, since the result gives qualitative information about the product to the user. If the user analyses a product and gets the final average result of ”2”, it then indicates that this product is possible to automate. However, if the user finds the average result to be ”6”, it indicates that it will be difficult and thereby expensive to automate the assembly process. A result like this is easy to interpret for anybody who knows the point scale and is thereby given a qualitative result. Furthermore, it is easy to identify areas of the product that do not fulfil the demands for easy assembly, and given the criterion it is fairly easy to understand how a preferable solution should be designed.

Drawbacks

The SINTEF method is, in some aspects, not specific enough to pinpoint certain automatic assembly difficulties. For example, there is no evaluation of a whole assembly sequence. Furthermore, there is no support in how to re-design the product if the evaluation shows poor results. Finally, there is no support for economic evaluation or comparison between alternative design concepts.

3.3.2 The DFA House

Rampersad (1994) presented a DFA method, called the DFA House that is based on a number of design rules. These design rules, or guidelines, are used to evaluate and quantify how well prepared a product is for automatic assembly. The design rules are based on Langmoen and Ramsli (1983) as described earlier, but also on Boothroyd and Dewhurst (1987). Each criterion is evaluated according to the point scale in Table 5.

Points	Description
1	Easy to automate
2	Less easy to automate
4	Difficult to automate
6	Very difficult to automate

Table 5: Point scale to indicate complexity level in automatic assembly (Rampersad, 1994).

Evaluation criteria for assembly properties

The design rules presented by Rampersad (1994) are structured in three different sections; assembly properties, Table 6, component properties, Table 7, and process properties, Table 8.

Assembly properties				
Criteria	**Points**			
	1	**2**	**4**	**6**
Weight	0,1 g <G≤ 2000 g	0,01 g ≤G≤ 0,1 g or 2 kg <G≤ 6 kg	G< 0,01 g or G> 6 kg	
Length	5 mm <L≤ 250 mm	2 mm ≤L≤ 5 mm or 250 mm ≤L≤ 2 m	L< 2 mm or L> 2 m	
Total number of components	< 20		>20	
Unique components	< 10		≥ 10	
Base components	With		Without	

Table 6: Qualitative evaluation criteria for assembly properties (Rampersad, 1994).

Evaluation criteria for component properties

The criterion continues with how to design a component (only a selection of the criterion are shown here).

Component properties				
Criteria	**Points**			
	1	**2**	**4**	**6**
Stiffness,	Non-flexible components		Flexible components	
Component size, not round, Lenght, L	5 mm<L≤ 500 mm	2 mm ≤L≤5 mm	L<2 mm or L>2 m	
Component symmetry, round	α & β symmetric	One of α or β symmetric, and the other asymmetric	α & β asymmetric	
Component symmetry, not round	180^{o} symmetric about more than one axis	180^{o} symmetric about one axis	Non-symmetric	
Tolerance, $S=D_1-D_2$ between peg and hole	S> 0,5	0,1 ≤S≤ 0,5	S <0,1	
Joining method	Snap, screwing and adhesive bonding	Peg-hole (press fitting), welding, soldering and retrieving		

Table 7: Evaluation criteria for component properties, after Rampersad, 1994.

Evaluation criteria for process properties

Finally, the evaluation criterion for the process.

Process properties				
Criteria	**Points**			
	1	**2**	**4**	**6**
State during feeding	Parts can not overlap or tangle		Parts can overlap or tangle	
Composing direction	Top-down	Side-in	Bottom-up	Others
Holding down during insertion	No	Yes		
Alignment	Chamfer		No chamfer	
Resistance to insertion	F<20 N	20 ≤F≤ 60 N	F >60 N	
Composing movement	Straight line movement	No straight line movement		

Table 8: Evaluation criteria for process properties (Rampersad, 1994).

Rampersad uses the evaluation criteria to get an overall score in a spreadsheet, which then can be analysed on the basis on suitability for automatic assembly. There is an objective value for each criterion, which is used for multiplying each score with, and thereby each criterion is, in a sense, weighted. For example, criterion ”number of different components” is much higher weighted than ”alignment”, according to Rampersad (1994).

There are more research results in this category, and Hsu *et al* (1998) presents one of the more recent ones. Their approach is to use design rules in a CAD system (PRO/Engineer) to incorporate DFA analysis to guide the designer while using the CAD tool. The design rules used are, according to Hsu (1998), based upon the work of Boothroyd and Dewhurst (1987) and Rampersad (1994). But, as already discussed, Rampersads work is partly based on Langmoen (1983). The point based scale is the same as used by Rampersad, see Table 5, and the design rules presented by Hsu are in most cases identical to the ones presented by Langmoen. But, being able to include these design rules into a CAD system, there is a need to take away those criteria that are not quantifiable or try to quantify those that are not.

All the above described evaluation criteria are examples of qualitative criteria. By evaluating a product according to these criteria, the user is automatically aware of what solution that is the preferred and can hopefully change the design.

Drawbacks

The DFA house is, similar to the drawbacks with the SINTEF method, not specific enough to pinpoint certain automatic assembly difficulties. For example, there is no evaluation of a whole assembly sequence. Furthermore, there is no support in how to re-design the product if the evaluation shows poor results. Finally, there is no support for economic evaluation or comparison between alternative design concepts.

3.3.3 The Hitachi Assembly Evaluation Method

The Hitachi Assembly Evaluation Method, AEM, is developed by Hitachi as a result of trying to develop an automatic assembly system for a tape recorder mechanism (Hashizume *et al*, 1980). After years of improvements, the ”new” Assembly Evaluation Method from Hitachi, was presented by Miyakawa (1990). The improvements were e.g. improved assembly cost estimation accuracy for individual parts.

The method does not distinguish manual, automatic or robotic assembly. The reasons are that the method is most beneficial when used in an early conceptual stage and the manufacturing method has not yet been decided. Miyakawa *et al* (1990) argues that there is also a strong correlation between the assembly difficulties for all three types of assembly methods.

Two indices

The base of the method is ”one motion for one part”. All operations are analysed and given points, where an unwanted operation is rewarded with fewer points than a preferred operation (Leaney and Wittenberg, 1992). An assemblability index is calculated by summarising the scores for all parts.

There are two indices in the AEM that highlights a products weakness:

- Assemblability evaluation score, ”E”
- Estimated assembly cost ratio, ”K”.

The assemblability evaluation score, E, assesses the difficulties of assembly operations, or the design quality. In AEM, the term assembly only refers to the insertion or fixing process. There is no analysis of the operations prior to insertion (Leaney and Wittenberg, 1992).

The estimated assembly cost ratio, K, is a relative index that compares any redesign to the estimated assembly cost of the original design. Therefore the original design score is always 100 (Leaney and Wittenberg, 1992).

Analysis procedure

An analysis procedure starts by determining an assembly sequence and then categorising each part according to ”standard operations”. There are about 20 standard operations for motions required to insert a part in the AEM. The ideal insertion process is a one-motion downward movement. All other operations receive a penalty score proportional to the difficulty of the operation, i.e. assembly operation cost or assembly time. An ideal operation is rewarded with 100 points since penalty score is zero. All scores are summarised and divided by the total number of parts. A product score of 100 would represent an assembly where every part is assembled with only simple downward motions. A target score is 80 or more (Egan, 1997). A product with an assemblability evaluation score ”E” of 80 or more is, according to Hitachi, possible to assemble fully automated at a justified cost (Miyakawa and Ohashi, 1986).

The assembly cost ratio ”K” is then calculated for the new design to compare the relative assembly cost of the new design to the original. A ratio of 0,7 or less is recommended (Egan, 1997). This equals an assembly cost saving of 30 % from the original design.

Improvement of the product

The assemblability evaluation score E is used as a guide for redesigning a product. However, both indices are required since a high E score can be achieved by having many simple components. The K score would then show the increasing costs due to increasing part numbers.

Drawbacks

The AEM method is focused mainly on the insertion process, which leaves a lot of questions unsolved. By focusing only a part of the whole assembly sequence there is a risk of sub optimisation of the product design. Furthermore, there is no support in how to re-design the product if the evaluation shows poor results.

3.3.4 The Sony DAC method

Design for Assembly Cost-effectiveness, DAC, is a method developed by Sony (Yamagiwa, 1988). After having rationalised manual assembly as far as thought possible, Sony started automating assembly operations. Problems in automation were due to the fact that products were too complex and too difficult to assemble automatically. Sony then started developing DAC to be able to adjust products for automatic assembly. The goal is to design products that are easy to assemble, preferably with the Sony SMART cell (see Fujimori (1990) for further description), an automatic assembly cell sold by Sony (Karlsson, 1995).

Working with the method

DAC is based on approximately 30 design rules or requirements, (Karlsson, 1995). Product evaluation is performed in comparison to how well the product fulfils a design rule or requirement. Maximum score is 100 points for each requirement. If a product does not fulfil a requirement it is rewarded with fewer points than 100. The 30 requirements are divided into handling (about 10 requirements) of the part and fitting of the part (about 20 requirements), (Karlsson, 1995).

The scores from evaluating a product are summed up to give an overall score. A score can be interpreted as in Table 9.

Points	Type of assembly
0 - 30	Automatic assembly is not possible. Manual assembly required.
30 - 70	Special machines are required for automatic assembly.
70 - 100	Standard machines, such as robots, can perform the assembly.

Table 9: The score in DAC indicates the type of assembly required, (Karlsson, 1995).

As results from a DAC evaluation are five measures. These measures can determine, from an assembly point of view, what design is better (Karlsson, 1995):

1 Assembly efficiency
2 Process time
3 Part count or number of screws
4 Process time per part
5 Average score

Assembly efficiency is calculated using two variables: total score and total number of parts. Only the relative comparison to other products is interesting. Process time is an estimated time for total assembly time if the product was manually assembled. Process time per part is the process time divided by the number of parts that are not fasteners. Average score is the overall score from analysis of each part.

Improvement of the product

It is possible to redesign a product according to the design rules used for the evaluation. One of the goals of DAC is to automatically educate designers in how bad designs can be avoided.

Drawbacks

The DAC method is focused on automatic assembly difficulties, but in some aspects the assembly sequence is less important. For example, the order in which certain operations are carried out may not influence the evaluation result. This indicates a lack of overview in the DAC method. Furthermore, all the focus is on individual parts and not on a whole product or module. Finally, the DAC method is aimed at supporting design teams to develop products that are easy to assemble in one specific assembly system, the Sony smart cell.

3.4 DFA methods with quantitative evaluation

There are several methods that use quantitative evaluation, but here only the fundamental principles will be exemplified and discussed for a few different methods.

3.4.1 Boothroyd and Dewhurst DFMA

One part of the Boothroyd and Dewhurst DFMA is the DFA method. There are DFA methods for manual, robotic, automatic and printed circuit board assembly available from Boothroyd and Dewhurst Incorporated, BDI. The most well known and most used DFA method is for manual assembly.

The manual DFA method is based on a database of estimated assembly times from a motion-time-measurement (MTM) study. The database contains estimated assembly times for different assembly operations. Every assembly operation depends on the design of a part and how it is assembled. By analysing how a part is handled and inserted, an estimated assembly time may be calculated.

A product or a drawing of the product is required to perform an analysis. Analysis is performed while assembling all parts of the product. Each part is analysed in two ways:

1 Possibility to eliminate the part.
2 Possibility to redesign the part to be easier to assemble.

Elimination/integration of parts

Reducing part count is an important step in this method. To decide whether or not a part is a candidate for integration or reduction, three questions are used (Boothroyd and Dewhurst, 1987):

1 Does the part move relative to other already assembled parts when the product is working in a normal way?
2 Does the part have to be of other material or isolated from other already assembled parts? Only fundamental material aspects are acceptable.
3 Does the part has to be separate from other already assembled parts because assembly or disassembly of other parts otherwise would be impossible?

If the answer to all these three questions is ”no”, the part is a candidate for elimination or integration.

Geometrical analysis of parts

The geometrical properties of each part are analysed. This analysis contains two steps. First, analyse how difficult the part is to handle. Second, analyse how the part is inserted while assembling. In each of these steps, the assembly process is used for comparing assembly movements with the estimated assembly times in the database. In this way, every assembly operation is quantified with an assembly time. In the method, the ideal handling time for a part, that is 1*1*1 inches, is 1,5 s and the ideal insertion time is 1,5 s. This sums up to the ideal total assembly time of 3 s for each part.

Any geometric feature that does not follow the ”ideal” design is ”punished” with a longer assembly time since it requires longer time to e.g. orient. Any extra operations, e.g. screwing, are also considered outside the ”ideal” assembly process and results in long assembly time.

Evaluation

All parts are analysed and the total assembly time for the whole product is added up as well as the theoretical decision of whether or not the part could be eliminated or integrated. This information is used to calculate an assembly index. The DFA index gives an overall measure of assembly efficiency. The formula for the DFA index for a whole product is (Boothroyd and Dewhurst, 1987):

$$\text{DFA - Index} = \frac{3 * \text{ Sum of theoretical minimum of parts}}{\text{Sum of total estimated assembly time}}$$

The figure ”3” in the formula is the ideal assembly time for handling and inserting a part. The index is a first indication of how well the product is prepared for assembly. Improving the assemblability and DFA index of a product can be done by elimination of ”unnecessary” parts and by redesigning parts to be easier to handle and insert.

Automatic assembly

It is also possible to analyse products for automatic assembly. This part of the DFA method is focused on high-speed assembly or robotic assembly. The main difference between these different foci is the flexibility (lower flexibility required in high speed assembly) and the cost of equipment.

Automatic assembly analysis is carried out almost as manual assembly analysis. When analysing products for automatic assembly, the estimated cost for automatic orientation, handling and assembling is given instead of estimated assembly times (Boothroyd and Dewhurst, 1984). There is also an average assembly cycle time as a result of the evaluation.

Improvement of the product

A low DFA index is an indication for redesigning a product. Parts that are not theoretically necessary should be eliminated. Parts that require high assembly times should be redesigned to better resemble the assembly process that requires the shortest assembly time.

Drawbacks

The BDI DFMA method is not primarily focused on automatic assembly difficulties. For example, there is no evaluation of a whole assembly sequence. An overall view of a product or module is missing. Furthermore, there is no support in how to re-design the product if the evaluation shows poor results.

3.4.2 The Lucas DFA

The Lucas DFA procedure was developed by University of Hull in conjunction with Lucas engineering. The base of the method is from the same research project as the Boothroyd & Dewhurst DFMA (Swift and Redford, 1978). Thus, the two systems have common features (Leaney and Wittenberg, 1992):

1. Reduce part numbers
2. Analysis of part geometry for the assembly process.

The method has one procedure for manual assembly and one for automatic assembly. Unlike the Boothroyd and Dewhurst DFA method no distinction is made between robotic and dedicated assembly systems.

Analysis procedure

Analysis with the Lucas method is based on an ”assembly sequence flowchart”, ASF. The method consists of assigning penalty points to potential assembly problems due to the design. These penalties are used to calculate three assemblability indices, called ”measures of performance”, MOP.

- Step one is functional analysis (Leaney and Wittenberg, 1992). Parts that perform primary functions (i.e. required by product specification) are categorised as type ”A”. Parts that only perform secondary functions (i.e. required by that particular design solution) are categorised as type ”B”, e.g. fasteners. The MOP ”Design Efficiency” is then calculated as A/(A+B). Design efficiency should exceed 60 %, (Egan, 1997).
- Step two is feeding analysis (Leaney and Wittenberg, 1992). This step is dependent on whether the assembly method is manual or automatic. For manual assembly a handling analysis assesses relative cost for handling each part. For automatic assembly the feeding analysis guides the user towards the appropriate feeding technology. The MOP ”handling ratio” is calculated as handling index divided by the number of essential A-parts. Target value is 2,5 or less, (Egan, 1997).
- Step three is fitting analysis (Leaney and Wittenberg, 1992). This analysis determines the relative cost for fitting each part. For automatic assembly an additional gripping analysis, which determines the ease of holding the part from where it is fed to the end of insertion. The fitting process consists of four parts: insertion and fitting, non-assembly operations, work-holding process and for automatic assembly, gripping. To carry out the fitting analysis the assembly sequence must be known and inserted into the flowchart, ASF. The MOP ”Fitting ratio” is calculated as the fitting index divided by the number of essential A-parts. Target value is 2,5 or less (Egan, 1997).

Improvement of the product

To improve the product designers need to eliminate all ”B” parts or combining them with an ”A” part. Parts with high indexes should be redesigned according to the evaluation criterion that equals the lowest score.

Drawbacks

The Lucas method is, in some aspects, not specific enough to pinpoint certain automatic assembly difficulties. An overall view on a product or module is missing. Furthermore, there is no support in how to re-design the product if the evaluation shows poor results.

3.4.3 Other examples

Sturges (1989) describes a way of quantifying manual dexterity (see also (Sturges, Kilani, 1992), (Sturges, Wright, 1989) and (Sturges, Yang, 1992)). The work is based on kinematics approach to human motions. The work is then summarised in a DFA calculator that assists the user to quantify an Index of Difficulty for each part or operation.

A result from this work is also a number of design rules for designing products for easy assembly, (Sturges, 1989). These design rules are somewhat similar to the ones aimed at automatic assembly, but somewhat less specified as for example: ”Has assembly dexterity been minimised?”, or ”Has the total parts count been minimised?”, (Sturges, 1989).

Sturges (1989) then argues that the Index of Difficulty can be interpreted as assembly time. Thereby, each index for a product is equal to its presumed manual assembly time. Adler and Schwager (1992) reports 12 % assembly costs reduction after redesigning the products as a result of using the DFA calculator by Sturges.

Other evaluation methods have been presented that are based on the manual assembly time database, for example the spreadsheets by Poli *et al* (1986). A spreadsheet is used to calculate a presumed assembly cost based on the design of the product.

3.5 What is missing?

Many of the quantitative evaluation methods have assembly time as measurement, as described above, for the product. To have information about presumed assembly time or cost could be very helpful, if the evaluation is accurate enough. However, no evaluation can include all parameters of assembly, and therefore the presumed assembly time or cost will always be somewhat uncertain.

One drawback in quantitative evaluation is that a result has to be interpreted in requirements for redesigning the product. There is usually no clear advice to the user for how to redesign a product with a low score. In a qualitative evaluation the evaluation criterion itself is an example of a way to improve the product if the best score is not fulfilled.

The use of qualitative evaluation is found in some of the described methods. However, in most methods, the use of design rules to inform the user of the method how to design instead is missing. It is one thing to identify what features in a product that does not fulfil certain requirements, but if the method is supposed to be used to design a prototype, i.e. there is nothing to evaluate yet, the use of design rules is preferable. Simply using the evaluation criteria as design rules is not enough. The design rules need to be more specific than the evaluation criterion to be useful.

The DAC method from SONY uses qualitative evaluation and the evaluation criteria are used as design rules. However, the design rules are too few and ”only” aimed at designing a product that can be assembled in a Sony SMART cell.

In conclusion, there is a need for a method that uses qualitative evaluation in combination with design rules that are general for any automatic assembly process. Furthermore, the support from economic evaluations is important for making design decisions.

3.6 Implications for this thesis

The overall approach of the DFAA method should be to support product development teams to understand how to design, not just tell them that this is a bad solution and therefore takes ”X” seconds to assemble. Therefore, the use of qualitative evaluation criteria is preferred, since they themselves contains information of how to do. A quantitative evaluation is mostly used when the prototype is finished and can be disassembled and analysed.

If Barton *et al* (1996) are right in that more than 70 % of the manufacturing problems are problems that have happened before, then why not try to avoid those problems in the first place. The problems are already built-in when the prototype is ready for evaluation. Therefore, the use of design rules in combination with qualitative evaluation as early as possible for designing the prototype can hopefully be a way to avoid some of these 70 % known problems.

The existing DFA methods are useful, but still there are areas where a new DFA method may contribute to improvement:

- Using an overall view on a product or module as well as focusing on individual parts.
- Analysing according to a generic automatic assembly sequence.
- Design suggestions if the evaluation result shows weaknesses.
- Cost evaluation or cost comparison between alternative designs.
- Possibility to use the DFA method early in the design phase, preferably even before there is a prototype.

4 Research aspects

There are several methods and tools for DFA, but they are not used as often as they could be. Despite lots of case studies showing significant improvements in total product cost, lead-time in manufacturing and so on (Ahm and Fabricius, 1990) there are, according to Egan (1997), few Swedish companies that systematically use any DFA technique. Egan, (1997) presents only six Swedish companies (Volvo, Whirlpool, ABB, Pharmacia LKB Biotechnology, Electrolux and Bofors Missiles and Systems) that use DFM or DFA and have some experience. Why does not more companies use DFA techniques? Is it because of the methods themselves or the users?

Usually, DFA analysis is performed only when the design details are known and the product is more or less finished. As a result, designers tend to view a DFA analysis as an extra step or burden (Hsu *et al*, 1998). To change this perspective, a new approach is necessary. A DFA analysis should be used to guide the designer or the product development team in the initial search for a ”good” design.

The research question in this thesis is (now more specified compared to the initial question):
How can a method for use in early product development, that focuses design for automatic assembly and includes both product evaluation and cost estimation, be structured and what information should it contain?

This thesis presents a new DFAA method that may be used in the early design stages to find an initial ”good” design. How can such a method be a support for product development from an empty drawing to the finished prototype? And note, the method must not require days or weeks of introduction and then be considered too complicated and therefore not used. The method is aimed at mechanical products.

4.1 Objectives and scope of this thesis

The objectives of this thesis are:

1 Based on the theories and experiences within the described problem area, a method should be proposed for product development that fulfils the requirements of creating products that are easy to assemble automatically.
2 Qualitative evaluation of products should be combined with design rules for designing products for automatic assembly.
3 A method that fulfils the needs expressed by companies should be created. This may increase the use of DFA in industry. A system for cost estimation should be included.

There are several DFA methods available today, but the focus is often on product evaluation and not on explaining how to avoid the features in the product where the evaluation indicates problems. The method proposed in this thesis, even though it also includes evaluation, is focused on describing how to avoid several known assembly problems. Further, the proposed method is supposed to be used early in the product development process, even before any prototypes exist. The method may be used to design the prototype.

Since there is a vast amount of research applicable on DFA and DFM as well as on areas related to those, there is a need to explain the scope of this research. This thesis focuses:

- How to design products for automatic assembly. Products designed for manual assembly are not prepared for automatic assembly, but products designed for automatic assembly will also simplify manual assembly. This may be further specified:
  - Evaluating products that are designed for automatic assembly (also useful for manual assembly). The evaluation is applicable for a generic automatic assembly process, with the aim to make it as simple as possible.
  - Using design rules to instruct the user of the method of how to avoid assembly problems and prepare the product to be assembled automatically.
- Supporting cost estimations in order to compare two alternative design concepts regarding the costs associated with each solution.

4.2 Research method

The research methods presented in this section will be further exemplified in section 5.

The research method may, according to Ejvegård (1993), affect the result of the research in many ways, from directly affecting the result to indirectly by influencing the data, Fig 14.

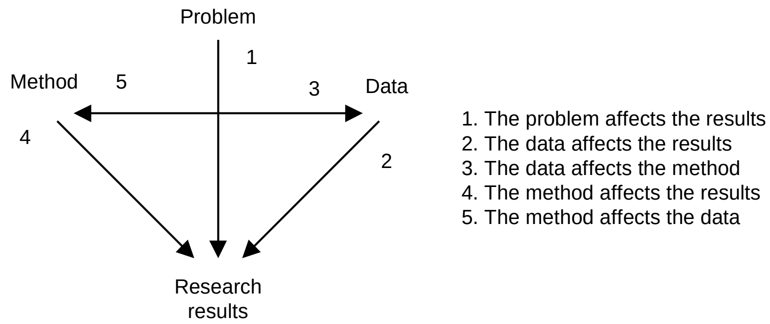


Fig 14: Research method affects the research result in several ways (Ejvegård, 1993).

If the research were conducted while being aware of how the result may be affected by the method, the result would be more reliable and valid.

Results presented in this thesis are based on different research approaches: ”case study research” and ”theoretical studies”. The major part of the research is based on theoretical studies, that is, the work of other researchers have been used to create a framework for describing the problem area and other attempts to a solution. For example, design rules and evaluation criterion in section 5 were identified in theoretical studies.

From the analysis of research results in the literature (facts observed through observation in Fig 15) in section 3, inductive research methods formed the rules and theories (e.g. use of design rules and qualitative evaluation) applied to solve the research problem. Based on the efforts and results from other researchers, conclusions have been drawn and new results have been proposed in sections 5 and 6. The ability to use results from others to explain and predict new results is an important characteristic of science (Chalmers, 1995) and is called deduction, Fig 15.

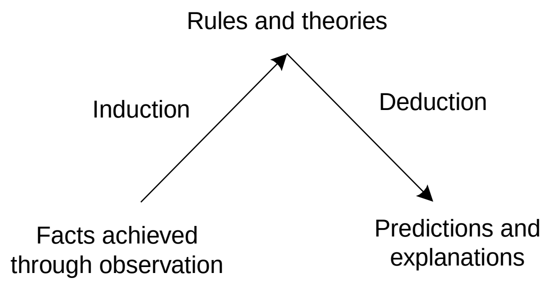


Fig 15: Induction and deduction, (Chalmers, 1995).

Parts of the thesis are also based on case study research. Case study research is a kind of empirical research that, according to Yin (1994):

- Considers a special situation that includes more interesting variables than information sources, and as a result
- Relies upon several sources, where data should converge since other results
- Can benefit from earlier results and conclusions of theoretical nature as support for collection and analysis of data.

Results from the case studies, comparable to ”finding facts through observation” in Fig 15, have, in attempt to solve the research question described earlier, see Fig 16, been used together with deductive research. According to Yin (1996) it is possible to make conclusions based on one or a few case studies. For example, the requirements (in section 5) on a DFA method were concluded on the basis of case studies. All the tests of the method were conducted as case studies, where the industrial participants were interviewed afterwards to give their opinion about the method. These results (both test results and opinions from design teams) were used for verification of whether the method fulfilled the requirements or not.

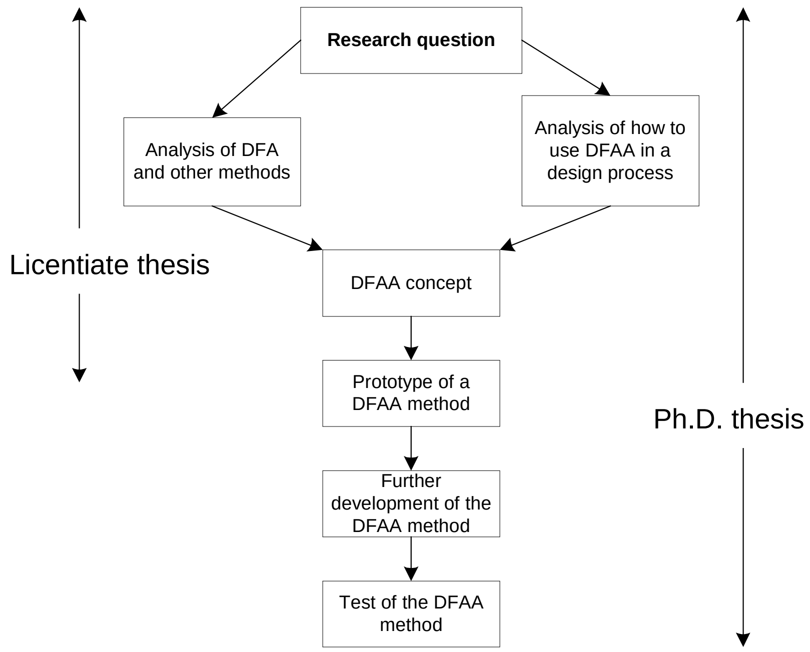


Fig 16: Contents of the thesis.

There are three different research method approaches according to Abnor and Bjerke (1994):

1. The analytical approach, which means that the final result is equal to the sum of all the parts, that knowledge is independent of individuals and that each part is explained through verified judgement.
2. The systematic approach, which means that the final result might differ from the sum of all the parts, that knowledge is dependant of the system and that the parts may be explained outgoing from the properties of the final result.
3. The actor's approach, which means that the final result only exists as structures of meanings, knowledge is dependant on individuals and that the final result is based on the actual background of the actors.

In this thesis, the systematic approach is most frequently used, described in Fig 17. This is because of the nature of the problem, e.g. how to structure the assembly sequence (described in section 5). However, the analytical approach is used to solve specific questions, e.g. how each evaluation criterion should be developed and used. Hence, a combination of the analytical and the systematic approach is used in this thesis.

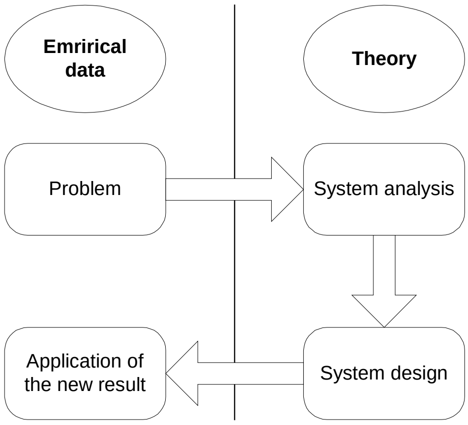


Fig 17: Model of system analysis as a research method (Abnor and Bjerke, 1994).

The problem was described in a prestudy, as seen in Fig 18, where the problem was defined (systematic approach) to form a frame of references. The frame of reference included studying other DFA-methods (analytical approach) to build the foundations for development of a new DFAA-method. The suggestion for a new DFAA-method was analysed to build a framework in which a solution was proposed. The proposed DFAA-method was analysed and used for conducting case studies in industry. The results from the case studies were analysed and the proposed method was improved to further meet the requirements from academia and industry. The results, the new DFAA-method, were described as DFA2 (the name is an alternative acronym to DFAA where the two A are replaced with A2), and openings for future research are possible.

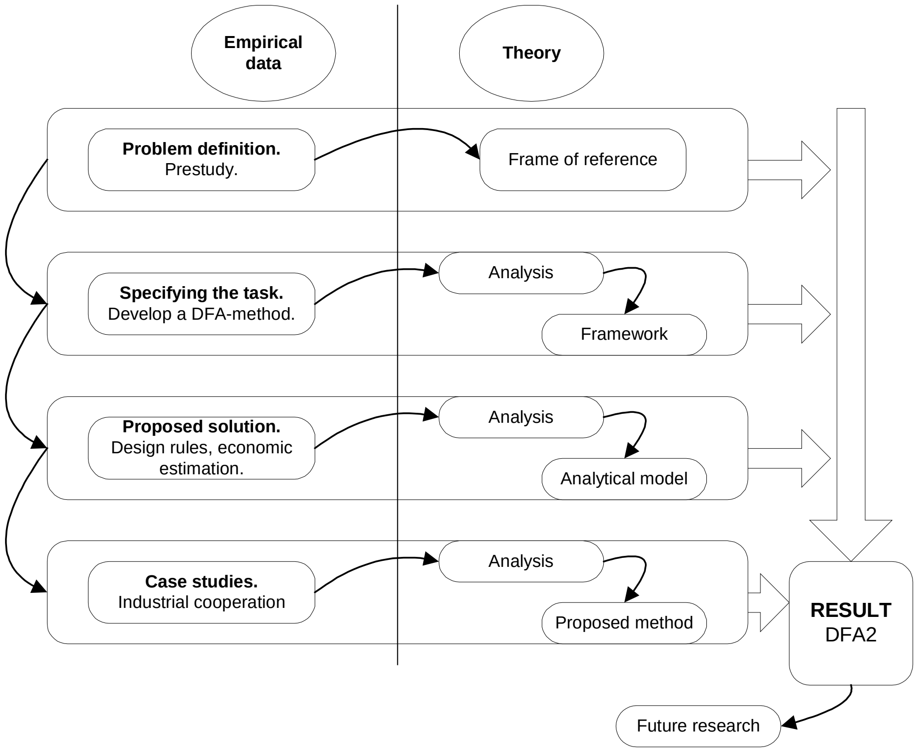


Fig 18: A flowchart describing the research approach in this thesis.

4.3 Academic contribution

By further exploring the field of DFA and especially DFAA, there will be new inputs and new aspects to the research community. Others may use some of the results of this thesis as input to their research.

First, this thesis constitutes one of the more comprehensive collections of design rules (found in this literature survey) aimed at automatic assembly. Thus, this thesis may be regarded at a source of knowledge in the field of product design for automatic assembly.

Among the academic contributions from this thesis are:

- Many have regarded the use of design rules in product development as more or less useless. Basically this is due to the lack of structure among the design rules. This thesis shows that design rules are of high value, especially if they are presented in a structured way.

- The use of qualitative evaluation is regarded as non-applicable in product development since the result usually is difficult to interpret. Applicability is a matter of presenting the evaluation results in a way that is easy to understand. This thesis shows that qualitative evaluation is useful in product development if it is combined with design rules and is put in a context.

- A lot of efforts have been made in the area of cost analysis. However, the use of activities and attributes in the way described in this thesis is somewhat of a new approach. Besides the cost estimations from the activity analysis, product design is brought closer to system design in a way that is beneficial for both areas of expertise. The step from product design to system design is short and displayed in this thesis.

4.4 Industrial contribution

Since the available DFA methods are not frequently used, something must be wrong. Regardless of whether the ”blame” is on product development teams or on the DFA methods themselves, something must be done. This thesis presents a method that, theoretically, fulfils the needs expressed by engineers in industry. This will contribute to increased knowledge and use of DFA methods, preferably the described DFAA method, in industry.

Among the companies participating in the DFAA-project, the knowledge about DFA has increased dramatically. Some of the companies are now working with introducing DFA2 as one method to be used in product development.

The participating companies were: ABB Automation Products, ABB Automation Systems, ABB Cewe, ABB Control, ABB Fläkt Industries, ABB Robotics, ABB Switchgear, BT Products, Electrolux, Ericsson Radio Access, Ericsson Radio Systems, ITT Flygt Industries, Modular Management, Rexroth Mecman, Scania, Volvo Car Corporation, Volvo Truck, Ångpanneföreningen, in total 18 companies.

Besides the companies that participated in the DFAA-project, other companies are interested in DFA2. The author has conducted training in the basics of DFA and tested the DFA2 method in more companies than the ones mentioned above.

If DFA2 is available as commercial software it is likely that even more companies will try the method and hopefully start applying it. The interest from companies for consultancy within DFAA has proven to be huge.

The use of activities for cost evaluation was very appreciated in many companies since it could help manufacturing engineers explain why and how a system must be configured a certain way based on product design. If product designers and system designer can use DFA2 to eliminate misunderstandings, shorten development times and lower costs, then this thesis is very valuable. One goal as a researcher is to find something that may increase the competitiveness of industry.

5 Development of a DFAA method

5.1 Automatic assembly: product requirements

To visualise the requirements for designing products for flexible automated assembly Gairola (1986) shows the relations between design features and assembly process features, Fig 19.

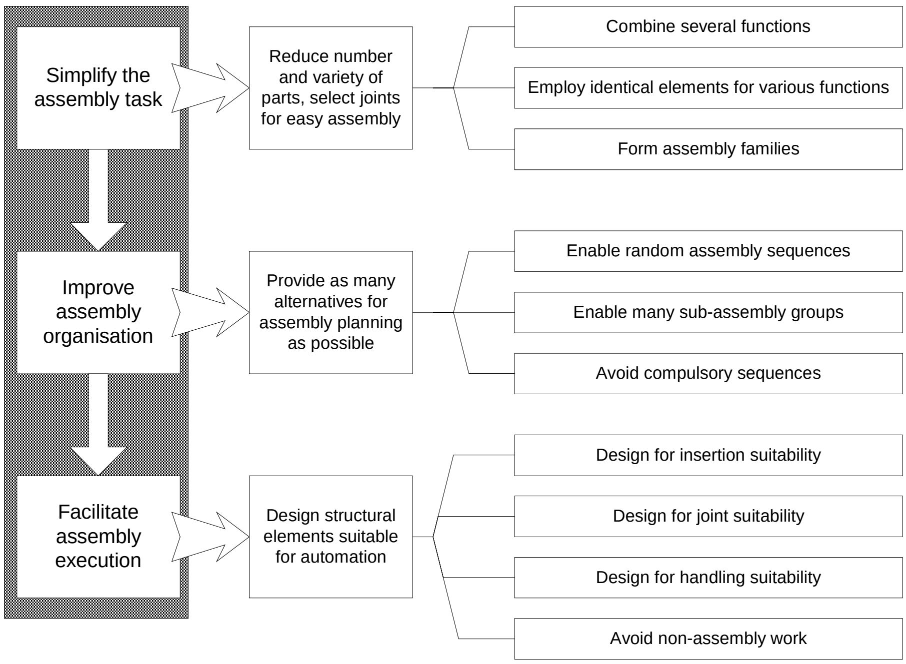


Fig 19: Requirements for design for flexible automatic assembly (Gairola, 1986).

Gairola (1986) states that is difficult to create a DFAA method, since the quality of aspects, to be accounted for is very large.

5.2 An ideal DFA tool - a case study

The DFAA method described in this thesis is based on a prestudy (Eskilander and Byron Carlsson, 1998). One major question relates to the requirements posed on an efficient DFA tool. The factors studied include:

- Tool design aspects.
- Tool application medium.
- Aspects the tool should consider (requirements).

If engineers in industry had the chance to wish how a DFA tool should be designed, what it should include and how it should be used, what would that tool look like?

The results from the prestudy (with five companies) suggested nine requirements on an applicable DFA tool (Eskilander and Byron Carlsson, 1998). The requirements are presented without relative order:

- Support cross functional teams
- Transfer of knowledge
- Cost analysis
- Quality assurance
- Geometric product evaluation
- Design suggestions
- Software
- Prohibit unnecessary variants
- User friendly

These requirements are very similar to the ones listed by Norell (1992). The only requirement stated by Norell (1992) that is not mentioned in the above requirements is that a DFA tool should contribute to a structured working approach (this requirement was implicit in the prestudy since the use of a formal DFA method was assumed).

<u>Support cross-functional teams</u>

Product development can no longer be considered a single designer’s task. A DFA tool must support the formation of a multi functional product development team. Unfortunately, some companies have the attitude that a single designer can handle the entire DFA analysis. Therefore, a DFA tool that clearly demands aspects that requires the knowledge and expertise from several disciplines, such as e.g. manufacturing engineers, quality engineers, sales engineers, is important.

Transfer of knowledge

A DFA tool should be able to record experience and knowledge from projects concerning how products should or should not be designed to fit this specific company. This knowledge can then be transferred to the next project and the company can avoid repeating mistakes, even if the people working in those product development teams have changed.

Cost analysis

The inclusion of quantitative analyses in cost predictions in the development of a given product is to be considered as a strong requirement. Having the possibility to compare two different solutions for a product, in terms of the costs incurred by the company, could bring manufacturing costs to become a deciding factor for design.

Quality assurance

How can we be sure that a product leaving the product development team to be manufactured is of good quality, i.e. the product is adjusted to the manufacturing system? To measure blue collar quality in a factory is not excessively difficult. The difficulty lies in measuring the engineer's performance. If a DFA tool can verify that the developed product does meet the requirements from the manufacturing system it can, in a way, guarantee the assemblability quality of the product.

Geometric product evaluation

Even if a cost estimation is important, a geometric product evaluation may underline the true product complexity for the manufacturing engineers. If the complexity of the product is high (in terms of required assembly processes), the automatic assembly system is likely to be expensive and unreliable. Therefore, a DFA tool should give an indication on how complex the product is, from an assembly point of view, in order to attempt to render it simpler and thereby requiring a less expensive assembly system.

Design suggestions

Most of the DFA tools available today are focused on, and effective with, product evaluation. However, no matter how good an evaluation is, there is always a need to know how to improve the areas where the evaluation showed poor solutions.

Software

Any respectable method should, for future engineers, be software based.

Prohibit unnecessary variants

The DFA tool must not sub-optimise the new products with regards to the rest of the product assortment. Creating solutions that result in extra and unnecessary variants must be avoided. Thus, a DFA tool must have an overall approach, or support the product development team to consider the rest of the product assortment while developing new products.

User friendly

The application and use of a DFA tool must avoid the need for extensive introductory courses. Furthermore, it must be simple enough for all participants in the team to understand and avoid aspects that are too obvious. The fact that not many DFA tools are used in industry could be connected to user unfriendliness.

5.3 Approach for the DFAA method

The nine requirements on a DFA tool described in the section above were used as goals to fulfil with the proposed DFAA method. The requirements ”transfer of knowledge” and ”design suggestions” seem to imply that a performing application of an efficient DFAA method could be applied in the form of design rules or guidelines.

5.3.1 Advantages and disadvantages with design rules

It is important to avoid the drawbacks in using design rules. Creating a list of design rules, or DFAA rules, is not enough to form a DFAA method. The sheer quantity of DFAA rules available renders it difficult to remember all the rules and to know which rule to apply in a specific context (Sackett and Holbrook, 1988). Egan (1997) argues that the use of design rules, as the ones presented by Scarr *et al* (1986), Baldwin (1966) or the ones presented in section 3.3, is disadvantageous because of three reasons:

- Applicability versus usability.
  Simple rules are often too general for any given problem and therefore not accepted or used. The number of rules renders it difficult to remember what rule to use when.
- No procedure for use.
  Although the rules contain useful knowledge, the lack of a procedure for how to use them in a structured manner reduces the usability.
- No quantitative design evaluation.
  Design rules only provide unstructured qualitative advice; however, in order to evaluate designs there is a need for a quantitative method.

The approach of using design rules provides the designer with qualitative descriptions of good design practice, Fig 20. The design rules represent guidelines for how to carry out product design, including steps for the avoidance of problems (Tichem, 1997).

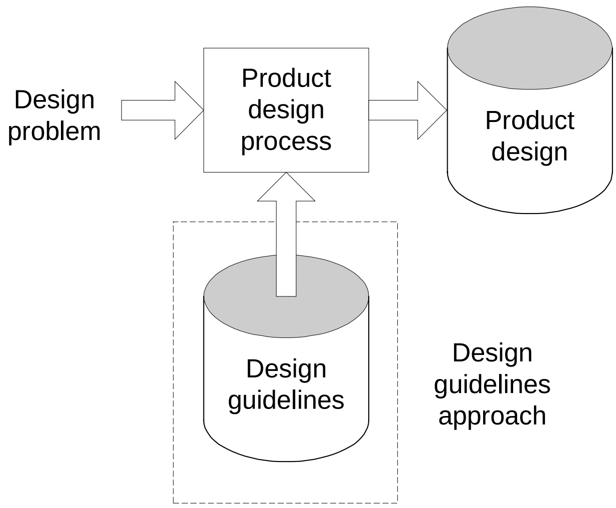


Fig 20: Schematic overview of the design rules approach, (Tichem, 1997).

The main advantage with the use of design rules is that they are usually relatively easy to understand. This can also be the drawback, since the design rules may be over-simplified for solving a specific design problem. Tichem (1997) further points out the following drawbacks in the use of design rules:

- The application of a specific design rule is left to the judgement of the designer: there are no mechanisms, which trigger the designer to select a certain design rule.
- There is no support in deciding when to implement a design rule or when to reject it.
- The translation of the design rule into information regarding the actual design is also left to the designer.
- Design rules seldom contain a quantification of the effects reached in applying a design rule.

Lee and Melkanoff (1991) suggest that design rules can be applied throughout the entire design stage, but the lack of a formal method in how to use them, and a mechanism to quantify the effect of prioritising one rule over another, limit their usefulness. However, there are examples where the use of DFM design rules has been used successfully (Edgington, 1989; Bässler, 1988). There are also other areas, for example designing for ease of recycling, where design rules are considered an appropriate way for meeting the specific recycling objectives (Beitz, 1993).

Kobayashi (1996) notes that one disadvantage with DFA methods is that they usually lack the ability to generate ideas for design improvements. Design rules, in combination with evaluation criteria, are thus believed to make a powerful combination. This combination allows the user to understand which alternative is to be preferred for automatic assembly, and also provide suggestions for its accomplishment.

The following potential disadvantages with the use of design rules have been identified, and the following solutions are suggested, Fig 21:

Potential disadvantage		Solution adopted
1	Applicability vs usability (Egan, Tichem).	Applicability: A structured way of applying the design rules. Usability: Mixing general and specific design rules.
2	No procedure to use (Egan, Tichem, Lee and Melkanoff).	A structured way of applying the design rules.
3	No quantitative design evaluation (Egan, Tichem).	Combining design rules with qualitative evaluation.
4	Translation of the design rule to the actual design (Tichem)	None, since the possible application of one design rule varies from one product to another.
5	Support in when to apply a design rule (Tichem).	A structured way of applying the design rules and economic estimations.

Fig 21: Potential disadvantages with using design rules and suggested solutions.

The method, in order to avoid the problems 1, 2 and 5 described in Fig 21 and render the DFAA method easy to use, understand, and applicable in many different companies, is structured as described in Fig 23.

The structure helps the user to focus on one aspect at a time, and ensures that the right information is discussed at the right time. The sequential structure also prevents any information from being overlooked when working with the method. The design rules in the method must not be too general by their nature, but applicable to specific details focused on automatic assembly (in order to further avoid potential disadvantage 1 in Fig 21).

The final potential disadvantage, number 3: “no quantitative design evaluation” in Fig 21 will be further discussed below.

5.3.2 Advantages and disadvantages with qualitative evaluation

Tichem (1997) notes the difference between stand-alone evaluation tools, see Fig 22, and the use of design rules, Fig 20.

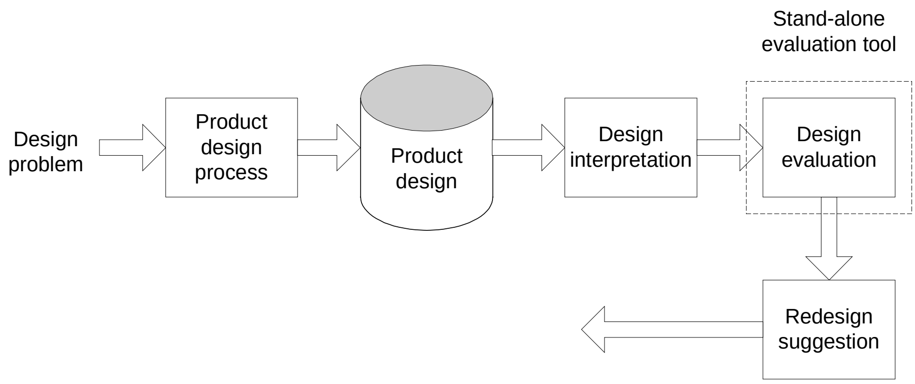


Fig 22: Schematic use of a stand-alone evaluation tool (Tichem, 1997).

In a design evaluation approach, the product design is analysed and the results are fed back to the designer. Evaluation methods require, according to Tichem (1997):

- Interpretation of the design, i.e. extraction of relevant features of the design. In existing tools the interpretation is often left to the designer.
- Analysing the design, i.e. evaluating the life-cycle properties of the design.
- Generating design advice. Today's tools often indicate the weak sections in the design, but suggestions for improving the design is left to the designer.

Here is also a clear distinction between qualitative and quantitative evaluation. Both evaluation philosophies can identify the weak aspects in the design. Qualitative evaluation also offers the potential of providing advices for how to correct the weak aspects. Quantitative evaluation does not offer this possibility (Tichem, 1997).

Finally, a qualitative evaluation has been included as a part of the method, such that it is possible to use in combination with the design rules. Since the evaluation criterion is included among the design rules the evaluation itself is one of the aspects that helps a product development team focus on a specific solution. Therefore, the design rules provide instant support in proposing ways to solve assembly problems outlined by the evaluation criterion. An overall index tells the user how far away from a product fully adapted to automatic assembly, according to the evaluation criterion, the proposed solution is. This evaluation procedure avoids the final disadvantage pointed out earlier, number 3 in Fig 21.

5.4 Evaluation philosophy for DFA2

As described earlier (in section 3), a qualitative evaluation philosophy is considered to be useful in the DFAA method, hereafter called DFA2 (DFAA is the area and DFA2 is the name of a method within this area). A qualitative evaluation criterion is, in itself, a guide to the process adapted solution. That qualitative aspect in evaluation is vital and should not be overlooked, since intended users of the method are supposed to avoid the unwanted solutions.

The evaluation criteria selected for DFA2, see appendix, are primarily derived from the criteria described in section 3.3. Each criterion is evaluated with a levelled points scheme:

- The best solution from an automatic assembly perspective is rewarded nine (9) points.
- An acceptable, but not completely satisfactory solution, from an automatic assembly perspective is rewarded three (3) points.
- A solution that is unwanted from an automatic assembly perspective is rewarded one (1) point. These solutions should be redesigned before the start of manufacturing.

Using the three levels 1, 3 and 9 is only a way of visualising the potential hazards of choosing a solution that is not perfect Although it might seem better to reward an unwanted solution with zero (0) points, this approach with the three levels (1, 3 and 9) is adopted in order to conform with the MFD method described in section 3. By following the same levels of evaluation the use of DFA2 within the MFD method is simplified.

The points from the evaluation are summarised at the end of the procedure. All solutions rewarded with points less than nine, the ideal point, entail that the user has a solution that is not perfectly adapted to automatic assembly. The total score of the product is divided with the maximum possible score, which tells the user, in percentage, how close to the ideal solution (with only nine points on every criterion) this product is.

$$100 * \frac{\text{Total score for the evaluated product}}{\text{Maximum ideal score}} = \text{DFA2 - index in \%}$$

Hence, a product rewarded solely with maximum points (nine), i.e. all evaluation criteria are met at the highest level, gets DFA2-index of 100 %. If a product is rewarded with only three points at each criterion, DFA2-index is 33 % and a product rewarded with one point per criteria gets DFA2-index of 11 %.

Note that only qualitative evaluation is used within DFA2, see appendix. However, the evaluation criteria may be interpreted as a quantitative measure representing how well the product is designed for automatic assembly.

5.5 Design rules and structure in DFA2

The core of the DFA2 method consists of a collection of structured design rules or guidelines, for designing products for automatic assembly, from over 30 years of literature in this field. The first step towards the DFA2 method was described in Byron Carlsson *et al* (1998) and has, since then, been further developed.

Since the method does not require a prototype, or an existing product to redesign, it can be used already at the start of projects. From an idea of how a product can be designed, preferably via modularisation, the DFA2 method supports product development teams in creating the first prototype. This first prototype should not come to require any drastic changes due to problems in the assembly process, since most of those problems should have been avoided while using the method.

The DFA2 method is structured and divided into two sections, one with design rules for the studied object (a module or a product), and the other section with design rules for each part of the module or product. The two sections are called product level and part level, Fig 23, and appendix.

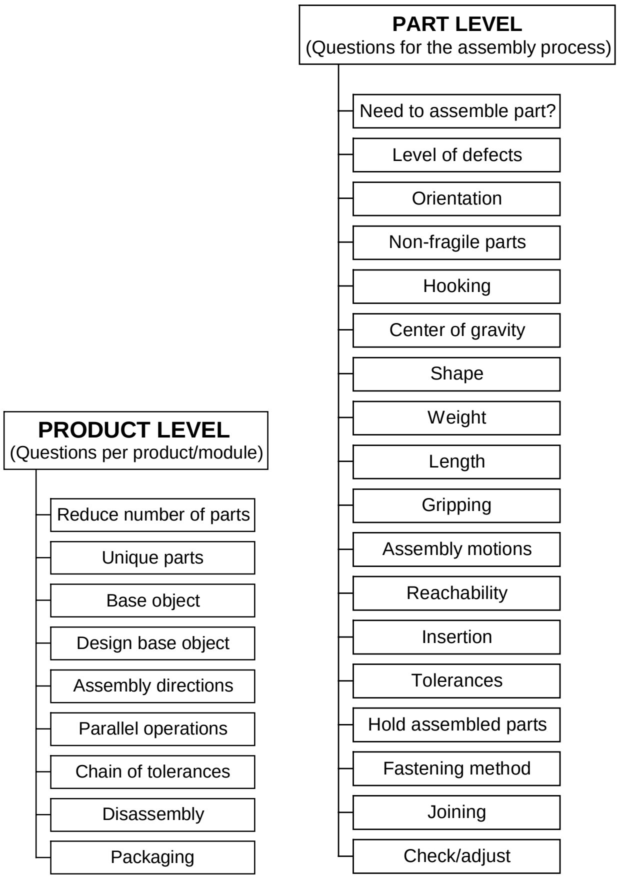


Fig 23: Suggested structure in the DFAA method.

5.6 DFA2 application

5.6.1 Design and evaluation during early product development

<u>Case 1</u>

Consider a new product that is first modularised with the use of the MFD method. The product developers now have a modular concept and proceed with detailed design of the module. The design team working with DFA2 should then start at the product level that contains design rules for the whole object. For example, the users can find design rules for how to design a base object and how to keep down the number of parts within the module. Since evaluation criterions are available for each set of design rules, it will be self-instructing on what solution is best suited.

When the product level design (or evaluation) is finished, the next step in DFA2 is to continue analysing and designing each part. Users of the method are given design rules that are structured in a generic assembly sequence, which even further focus on the assembly issues. The users are free (and recommended) to iterate back and forth in the method (both between product and part level as well as within each section).

Case 2

Consider now users that do not have a modular concept for the product (however, the preferred situation is to start from a modular concept). The product concept can still be treated in the same way as a modular concept, starting at product level. By applying DFA2 within a limited section of the product or a subassembly the procedure is still useful.

5.6.2 Redesign and evaluation of an existing product

In redesign, the structure of the object should be analysed before using DFA2. The product structure determines the assembly sequence, but DFA2 does not suggest a preferred structure or assembly sequence. Every object to be analysed has a given assembly sequence that starts with an initial part, called base object. All the remaining parts are assembled on the base object, without disruptions. If the object does not result in a given assembly sequence without disruptions, the object may be broken down into smaller objects, subassemblies.

Every object with a pre-defined sequence is first analysed at product level and then, subsequently, each part of the object is analysed at part level.

While working with the method, discussions and suggestions for redesign may be recorded together with the analysis result for documentation. Any new design rules derived from specific assembly equipment or other experiences should be added to the DFA2 method in order to prevent any mistakes to be repeated.

5.7 DFA2 index

The DFA2 index, derived as shown in section 5.4, is used as an approximate measure of performance. In order to fully establish the qualitative and quantitative potential of this DFA2 index, further studies are proposed. Empirical studies and the introduction of cost analysis (see section 6) in conjunction with the DFA2 index calculations are suggested.

The evaluation criteria in the proposed method are equally weighted. This approach has been adapted since their influence at practical process level is, to date, deemed as equally important. Weighting the criterion should be introduced if economical impacts are also to be included. This issue is further discussed in section 7.8.

5.8 Illustrative example of DFA2

To demonstrate how a DFA2 analysis may be performed, two existing bicycle bells are used as examples, Fig 24 and Fig 26. The evaluation was based on the evaluation criterion in Appendix.

Since the assembly processes are not known, assumptions about assembly sequence, part quality, how parts are delivered etc must be made. The DFA2 evaluation result for the first bicycle bell (“old” design) is described in Fig 25.

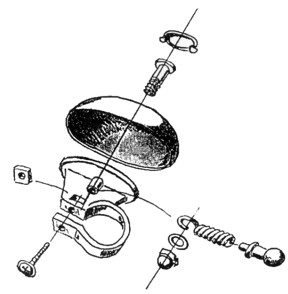


Fig 24: Old bicycle bell design.

	PRODUCT LEVEL							
	Reduce number of parts	Unique parts	Base object	Design base object	Assembly directions	Parallel operations	Chain of tolerances	**SUM**
Object/Product/Module	9	1	9	3	1	9	3	35

Part level

List of all parts	Number of identical parts	Need to assemble part?	Level of defects	Orientation	Fragile parts	Hooking	Centre of gravity	Shape	Weight	Length	Gripping	Assembly motions	Reachability	Insertion	Tolerances	Holding assembled parts	Fastening method	Joining	Check/adjust	**SUM**
Metal cupola	1	9	3	1	9	9	3	3	9	9	9	9	9	9	9	3	9	9	9	130
Long screw	1	1	9	1	9	9	9	3	9	9	3	9	9	3	9	3	9	9	9	122
Plastic top	1	1	3	1	9	9	3	3	9	9	9	9	9	9	1	9	9	9	9	120
Base unit	1	9	3	1	9	1	1	1	9	9	3	9	9	3	9	1	9	9	9	104
Square nut	1	1	9	1	9	9	9	9	9	9	3	9	3	3	3	1	9	9	3	108
Screw	1	1	9	1	9	9	9	3	9	9	3	9	9	1	3	3	3	3	9	102
Spring	1	9	1	1	9	1	1	1	9	9	3	9	9	3	9	1	9	9	9	102
Washer	1	1	9	1	9	9	9	9	9	9	3	9	3	1	3	3	9	9	9	114
Nut	1	1	9	1	9	9	1	3	9	9	3	9	1	1	3	1	3	3	9	84
Plastic knob	1	1	3	1	9	9	9	3	9	9	3	9	9	1	3	3	3	3	9	93

TOTAL SUM: 1079

$$\text{DFA2 index} = \frac{\text{Total sum}}{\text{Maximum points * number of parts}} \qquad \text{DFA2 index} = \frac{1079}{162 * 10} = 66{,}6\ \%$$

Fig 25: Evaluation sheet for the old bicycle bell.

From the evaluation results in Fig 25 it is obvious that the number of assembly directions in the product is too high. Furthermore, it is suggested that only three parts are theoretically necessary (marked with nine points) in the bicycle bell; the metal cupola, the base unit and the spring. Assumptions had to be made concerning the level of defects and orientation. The gripping evaluation reveals an unnecessary use of different grippers, whereas standard gripper surfaces would be recommended. Insertions of some parts may cause difficulties, partly because of several insertion directions but also due to narrow passages or lack of chamfers etc.

In an automatic assembly system, it is not a stable process if parts need holding during assembly, which shows in the evaluation. Fastening methods are snap fits and screwing operations, which in the case of screws needs special equipment to perform the operation. It is finally assumed that a control is needed to verify that the square nut is still in place before the screw may be assembled. Naturally, each criterion with score "1" and then "3" must be carefully considered regarding whether if it would be possible to improve or not. Could it be possible to re-design the bicycle bell with only three parts and at the same time take into consideration all the other aspects?

To demonstrate the differences in DFA2 evaluation results, a second bicycle bell was evaluated (also existing on the market). This bicycle bell could have been the result from re-designing the old bicycle bell. Assume that the following analysis was made to verify if the re-designed bell had been improved or not, from an automatic assembly point of view.

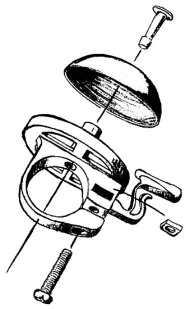


Fig 26: Bicycle bell after re-design.

	PRODUCT LEVEL							
	Reduce number of parts	Unique parts	Base object	Design base object	Assembly directions	Parallel operations	Chain of tolerances	**SUM**
Object/Product/Module	9	1	9	3	1	3	3	29

Part level

List of all parts	Number of identical parts	Need to assemble part?	Level of defects	Orientation	Fragile parts	Hooking	Centre of gravity	Shape	Weight	Length	Gripping	Assembly motions	Reachability	Insertion	Tolerances	Holding assembled parts	Fastening method	Joining	Check/adjust	**SUM**
Base unit	1	9	9	9	9	1	3	1	9	9	9	9	9	9	9	3	9	9	9	134
Metal cupola	1	9	9	3	3	9	3	3	9	9	9	9	9	9	9	3	9	9	9	132
Rivet	1	1	9	1	9	9	9	3	9	9	3	9	9	9	3	9	9	9	9	128
Square nut	1	1	9	1	9	9	9	9	9	9	3	9	3	9	3	3	9	9	9	122
Screw	1	1	9	1	9	9	9	3	9	9	3	9	3	9	9	9	3	3	9	116
																			TOTAL SUM:	732

$$\text{DFA2 index} = \frac{\text{Total sum}}{\text{Maximum points * number of parts}} \qquad \text{DFA2 index} = \frac{732}{162 * 5} = 90{,}4\ \%$$

Fig 27: Evaluation sheet for the re-designed bicycle bell.

From the evaluation results in Fig 27 it is obvious that the number of assembly directions in the product is still too high (three directions). Furthermore, it is suggested that only two parts are theoretically necessary (marked with nine points) in the bicycle bell; the metal cupola and the base unit. Assumptions had to be made concerning the level of defects and orientation. The gripping evaluation reveals an unnecessary use of different grippers, whereas standard gripper surfaces would be recommended. In this re-designed bicycle bell there are no longer problems with insertion, thanks to chamfers and elimination of narrow passages. In an automatic assembly system, it is not a stable process if parts need holding during assembly, and the evaluation reveals that the product is now acceptable. Fastening methods are snap fits and screwing operations, which in the case of screws needs special equipment to perform the operation. It is finally assumed that control for any of the parts is not needed.

As shown in Fig 25 and Fig 27 the DFA2 index increased from approximately 67% to 90 %. These indices may be used to verify that the re-designed bicycle bell is a lot better, from an automatic assembly point of view, than the old one. Several improvements were made, but still there are potential improvements on the re-designed bicycle bell. For example, three parts could theoretically be eliminated or integrated, part orientation could be improved and gripper surfaces could be added. The evaluation result may be used for assembly system design, since it contains a lot of information about the assembly process.

5.9 Product example

The product chosen to be redesigned with DFA2 was selected from the company “Easy Living”.

Easy Living AB develops and manufactures products for home automation since 1993. The company has developed a new local radio-based system (Easy-Net), planned to be put in production soon. Easy-Net is prepared for internet connection and is compatible with Ericsson’s *e-box*. With the release of Easy-Net, the sales volumes are expected to increase dramatically.

The market for home automation is immature, but the expectations for fast market growth are strong. This market development will lead to an accelerated product development and increased sales volumes. Easy Living wishes to automate the assembly of their products in order to meet the increased demands and attain better control of both production and storage. The company’s automation demands are:

- Sufficient capacity and quality levels.
- Possibility to assemble all existing and future product variants in the same system; presupposes consideration of the assembly process.
- Electronic administration.
- Produce complete customer orders.

- Reasonable investment cost.
- Movable and re-configurable assembly system.
- User friendly
- High-tech profile; adequate mental & physical environment.

Due to such requirements, Easy Living co-operates with KTH (Royal Institute of Technology) in the development of an assembly system based on the Hyper Flexible Automatic Assembly (HFAA) system principles, called Mark IV (Onori *et al*, 1999).

5.9.1 The products

The products are part of the Easy-Net family, Fig 28, and may be combined after customer needs. Easy Living has created a basic system, which can be expanded at a later stage.

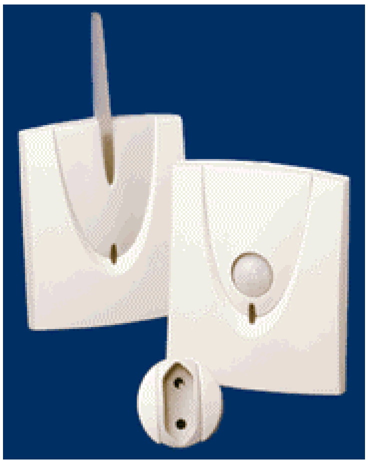


Fig 28: Products from Easy Living.

The basic Easy-Net system consist of:

- A radio-base with integrated micro-server (to the left in Fig 28).
- A sensor available in different variants e.g. motion-, temperature- and light detection (to the right in Fig 28).
- Four home controllers for light regulation (in the middle of Fig 28).
- A remote control (not in Fig 28).
- A Windows application for easy regulation and supervision of Easy-Net.

Product sizes are: radio and sensor 100 * 100 mm; home controller: diameter 45 mm and height 70 mm. The products weigh approximately 0,1 kg.

5.9.2 Using DFA2 to improve the product

Extensive work has been carried out to adjust the products for automatic assembly. This work has been carried out in co-operation with product developers, production engineers at Easy-Living and the research team at KTH/IVF (Royal Institute of Technology and The Swedish Institute of Production Engineering Research).

The home controller II (HC-II) from the Easy-Net was selected to be analysed and improved with DFA2. The original HC-II design, Fig 29, contained 16 parts and had a DFA-index, using the Boothroyd and Dewhurst DFMA method (Boothroyd and Dewhurst, 1987), of 10 %. The DFA2 index was 59 % and the analysis identified several potential improvements.

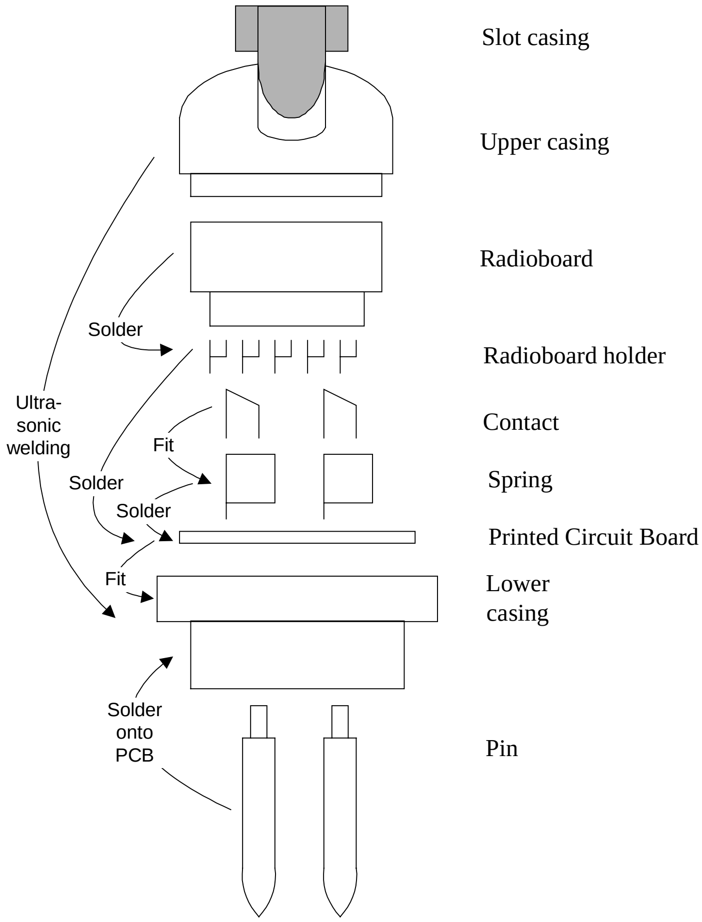


Fig 29: HC-II before redesign.

The product was first analysed using the product level of DFA2. For example, the two assembly directions (pins from below added a second direction) and the design of the base object were given low scores and suggested for redesigned. One assembly direction is preferable according to the evaluation criterion in DFA2.

Finally, each part was analysed using the part level of DFA2. For example, the number of parts, the gripping of parts, insertion of parts and fastening method were given low scores. According to DFA2 the number of parts should be reduced, the parts should be gripped in a standardised way, the insertion should be facilitated and simpler fastening methods should be chosen.

Design changes suggested with support from DFA2 method included:

- Snap-fits instead of soldering and ultrasonic welding.
- Pins integrated to lower casing (injection moulding).
- Reduction of the number of parts, radio board holders and springs.
- Standard gripping features in the parts eliminates the need for gripper changes.
- Chamfers and guides to support and simplify insertion of parts.
- Integration of PC- and radio board

The analysis also resulted in a reduction of parts from 16 to 6, a total reduction of 62,5 %, Fig 30. The DFMA-index was improved to 40 % and the DFA2 index to 77 %.

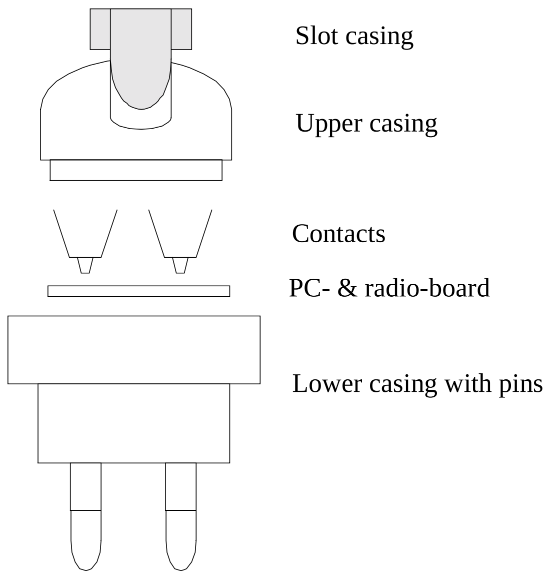


Fig 30: HC-II after redesign.

The design changes enabled automatic assembly. The cost for today’s manual assembly of HC-II will be greatly reduced when the Mark IV assembly system is installed.

Despite the fact that the HC-II is patented world wide for its electronic design, it was possible to make large improvements as described (integration of PC- and radio board, pins and lower casing, etc.).

Experience from the DFA2 work with HC-II led to further work on the other products in the Easy-Net family. This ensured that the radio-base and sensor in the Easy-Net system could be designed efficiently the first time. The DFMA-index is 78 % for both products. Hence, DFA2 was shown to enable transfer of knowledge between projects and increases the designers' skills. For example, surfaces for easy handling of parts during assembly were designed from the beginning. As a result, the radio, the sensor and the remote control assemblies (total of 15 different parts) need only one simple conventional linear gripper. This gripper may turn out to be a standard within the company.

Furthermore, working with DFA2 encouraged close collaboration between product designers and system designers.

Other aspects:

- Why was modularity left out?
  In-house competence and available project time. Project succeeded anyhow, showing that DFA2 is not dependant on MFD.
- How did Easy living react to the re-tooling costs?
  They had not considered this possibility/cost. The savings achieved in other areas, and the possibility to assemble automatically overweighed this problem.
- How long did it take to learn and use DFA2?
  One week. DFA2 was considered very easy to use and apply! Easy to show designers WHY changes are required (visual structure).
- How did the sub-contractors react?
  No problem. Pins in lower casing gave sub-contractor more work ($) without increase in complexity.

5.10 Example of DFA2 test results

Results from other cases where DFA2 were used in industry are not possible to describe in detail due to confidentiality. However, a general overview of a few results and some specific improvements may be described:

Case 1: A physically large product in few variants that presently is manually assembled.

- The number of parts could be reduced with approximately 30 %.
- Fewer part variants, e.g. two variants of a part (assembled left or right) could be integrated into only one part that could be assembled on either side.
- Several chamfers or other similar measures to simplify insertion were suggested for re-design.
- Only two different fasteners could be used after re-design compared to four in the existing product.

Case 2: A module, common for several other products, available in few variants and presently assembled manually.

- The number of parts could be reduced with approximately 30 %.
- Part properties to facilitate automatic feeding (vibration feeders and magazines) could be included after re-designing the parts.
- Standard surfaces could be integrated in the re-designed parts to allow only three grippers to be used.
- Separate fasteners could be dramatically reduced and snap fits applied instead.

Case 3: A module in a product family, available in a couple of variants presently assembled automatically.

- The number of parts could be significantly reduced.
- The different types of fasteners could be significantly reduced.
- The DFA2 analysis identified especially one specific part to cause assembly difficulties. This was verified by the system performance measures since that particular part often caused the system to stop. The DFA2 analysis results were used to explain why the difficulties occurred and how to avoid them after re-design.
- When analysing the product level with DFA2, a new concept for structuring the product was suggested by the design team based on the analysis results.

Case 4: A module in a product family, available in a couple of variants presently assembled automatically.

- The number of parts could be significantly reduced.
- The different types of fasteners could be significantly reduced.
- The assembly sequence could be changed to simplify the assembly process after re-design.
- Insertion and fastening of parts could be simplified after re-design.
- The DFA2 analysis result was used for a discussion on how to modularise the product.

6 Economic evaluation

This chapter begins with a frame of reference within economic models useful for DFA purposes. Based on others research, a suggested model for economic evaluation is presented.

6.1 Different approaches

As discussed earlier, it is possible to foresee how product design (including all activities for designing a product) will influence the assembly process. Unfortunately it is not as simple to foresee how the product design will affect the costs for manufacturing. However, since a major part of the manufacturing costs are determined during the design phase, there is an underlying need for methods to estimate these costs. The ideal situation, in a product development project, would be to have reliable estimations of the manufacturing costs in order to compare alternative product concepts.

Many researchers have tried to find a method, or model, for cost estimations, as described in an extensive survey by Gupta and Chow (1985). Naturally, there are several possible ways of estimating costs; Ulrich and Fine (1990) suggest the following approaches:

- Reliance on the engineering judgement of the design team members.
- Using the service of an expert estimator.
- Using a computer program that implements the calculations and/or rules of an expert estimator.
- Assembly-driven design for manufacturing.
- Design for total life cycle costs.

6.1.1 Engineering judgement

One of the most commonly used methods for influencing design choices with manufacturing cost information is by applying the judgement of experienced engineers. Based on earlier experience, a design team may use their acquired knowledge about manufacturing costs to influence the product design. This approach is often used in small and medium sized companies.

A drawback is that the result of this method depends on the individual capacity of those involved in the design team as well as on their experience.

6.1.2 Expert estimator

Larger companies may employ an expert estimator. This estimator usually needs a more or less finalised engineering drawing of the product. The results are often based on direct labour, machine time and investment costs. By adding a given percentage to the sub-total, the overhead costs are included.

The main drawbacks of this method are the time needed for the estimations, the quantity and accuracy of data required for the estimations, and the estimation methods applied.

6.1.3 Software using estimators experiences

This method is an extension of the previously described method. In this case, the estimator has automated some of the steps through software applications. This allows the estimation time to decrease and the possibility for engineers to generate several alternatives simultaneously. The drawbacks are similar to those for expert estimator, described above.

6.1.4 Assembly-driven design for manufacturing

There are many methods within assembly-driven design, on how to evaluate the costs and allow two designs to be compared. These methods rest on the assumption that improving the ease of assembly of a product will result in designs that are improved for other manufacturing aspects as well.

The primary weakness of these methods is that they view manufacturing costs as being primarily driven by assembly costs.

6.1.5 Life cycle costs

The ideal cost information for a design phase would be a life cycle cost (LCC) estimation. This approach could, theoretically, produce cost information about direct material, direct labour, product development, tooling, quality, purchasing, manufacturing engineering, inventory control, quality control, maintenance, disassembly, recycling etc. Knowing how a design decision influences the whole life cycle could drastically affect, and alter, the way products are designed.

However, the information needed is extensive and the estimations may require different levels of detailed engineering drawings. Moreover, the results might be somewhat general and uncertain. Since it is difficult enough to achieve design teams that produce cost estimations that are simply focused on manufacturing, the perspective of having a model applied to an entire life cycle becomes overwhelming. Extensive research is therefore being conducted in this area and it is foreseeable that these techniques will be available for design teams in the future.

Kolarik (1980) describes three general LCC models:

- Conceptual
- Analytical
- Heuristic

Conceptual LCC models

Conceptual models are usually focused on the macro level. They typically consist of a set of hypothesized relationships expressed in a qualitative framework (Kolarik, 1980). A conceptual model may suggest that the costs consist of research and development, investments (machines etc.) and operations.

Most conceptual LCC models are not highly mathematical or formal, but are valuable aids in stimulating the thought processes. Applicability, as detailed by Kolarik (1980), is low for detailed design decisions. Tipnis (1993), Shields and Young (1991), Fabrycky (1987) and Lee and Melkanoff (1993) also describe conceptual LCC models.

Analytical LCC models

Analytical LCC models typically consist of a set of mathematical relationships, which are used for describing a certain aspect of a system. In many cases the analytical LCC models are based on a number of assumptions, which tend to limit the ability of the model to reflect the actual system performance (Kolarik, 1980). The models vary in their mathematical sophistication and many models have been presented; Gupta and Chow (1985) alone report about 667 references. Wilson (1986) describes a type of model for cost estimation, which Dighton (1980) describes its use in designing the Hornet aircraft at McDonnel Douglas Corporation. Dean (1995) details how NASA works with LCC. The military early adopted LCC applications, as described in Caver (1979).

One of these LCC techniques is called the parametric cost model. Parametric models rely on simulation models, i.e. statistically and logically supported models (Dean, 1995). A typical parametric model:

$$Cost = f(x,p) + e$$

where x and p are parameters and e is the prediction error as described by Dean (1995).

A weakness of parametric cost estimation is its low applicability to products consisting of new technologies. Parametric cost estimation is often referred to as a “top-down” technique and usually treats the product at system level and not at part level (Asiedu and Gu, 1998). Daschbach and Apgar (1988) describe the importance of correct estimations since both over- and underestimates could lead to problems.

Heuristic LCC models

Heuristic models are usually developed through computer simulation techniques (Kolarik, 1980). The simulation allows analysis of “what-if” situations. Since heuristic models are not as general as analytical models, they may usually only be used for a specific situation. Sometimes, heuristic models are referred to as poorly structured analytical models that do not guarantee an optimal solution (Asiedu and Gu, 1998).

6.1.6 Summary and selected approach

Based on the approaches described above, assembly driven design for manufacturing is selected for further work. Since the aim of this thesis is to find a method for cost estimation that focuses on the assembly process in order to support the rest of the DFA2 method, the selected cost estimation approach is the assembly-driven design for manufacturing, further discussed in section 6.2.

6.2 Cost estimation models for DFA

A design team basically needs a relationship between cost information and design decisions. Preferably, this cost information should be made available during the design phase, for immediate feedback, and not as a separate analysis after the design is finalised.

The cost estimation models discussed below all focus on manufacturing costs, but could also be part of a larger life cycle cost model.

Wierda (1988) discusses the following cost estimation methods:

- The weight method
- Method of materials costs
- Dimensioning method
- Cost functions
- Cost increase functions
- Function costs
- Relative costs
- Product classification
- Times and rates

Besides these nine methods a tenth technique, often used for life cycle cost methods, is useful in this thesis:

- Activity based cost estimations

A survey showed that the companies participating in the DFAA-project used the estimation methods as described in Fig 31 (all companies were asked what cost estimation methods they used). The methods will be detailed below.

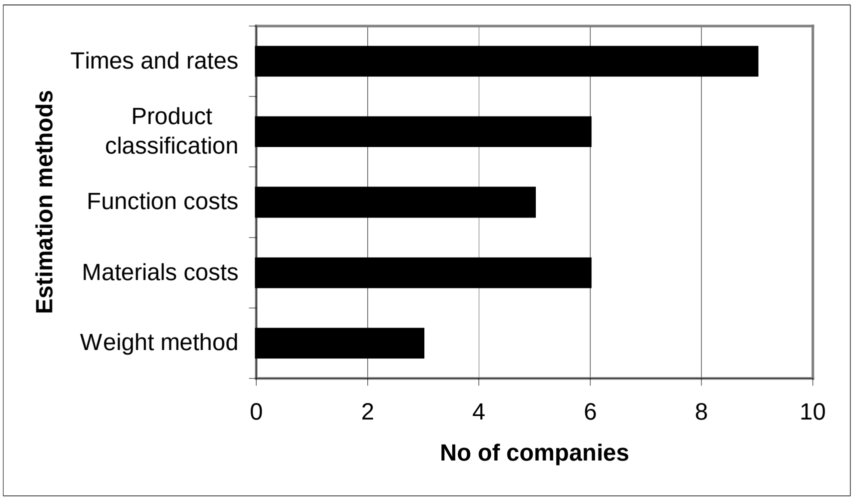


Fig 31: The cost estimation methods applied within eleven companies participating in the DFAA-project (some companies used more than one method).

6.2.1 The weight method

This method is based on the relationship between manufacturing costs and the weight of products within a certain class. The products must be rather similar within this class (similar in design and manufacturing), to ensure a sufficiently accurate estimation.

Assume that a given car costs 100 SEK/kg to manufacture. The manufacturing costs for a new model may then be calculated on this basis. Even though this estimation is very uncertain and not very accurate, it is still frequently used as described by Wierda (1988) and Pugh (1974). A survey among the companies participating in the DFAA-project showed that three out of eleven companies (27 %) use this method (often as a complement to other methods).

The applicability of the method is, however, low in detailed design decisions since it only suggests that the use of materials should be minimised (or lighter materials used).

6.2.2 Method of materials costs

The ratio of material costs to the total manufacturing costs may be calculated and within specified groups of products considered constant (Wierda, 1988). Basically, the method produces an estimate of the total costs based on the known materials cost for the given product.

This method, as with the weight method, is limited in use for products that are similar in design and manufacturing. However, although it results in only crude estimates, a survey among the companies participating in the DFAA-project showed that six out of eleven companies (54 %) used this method (often as a complement to other methods).

The method suggests that cheaper, or less materials, should be used, and therefore the applicability of the method in detail design decisions is low.

6.2.3 Dimensioning method

This method combines technical and economical parameters into one equation (Wierda, 1988). The method requires parameters such as hole diameter, hole depth, wall thickness and ratios such as processing costs per unit of area etc. This information is then used in cost equations where the design team may quantify certain parameters. The complexity of the method, and lack of evident relations between the product parameters and costs, has limited the use of this method (Wierda, 1988).

6.2.4 Cost functions

A more transparent and easy to use method (compared to the method described in section 6.2.3) is the cost function. The cost function will differ from company to company and for different machines because of different prerequisites. Cost functions are usually the same approach as the parametric cost model described in the LCC section, but often applied at part level.

Basically, the cost function uses selected parameters that are thought to influence the cost of a product (e.g. dimensions, tolerances, number of parts etc). The influence of these cost parameters in existing products are plotted and analysed. Finally, the influence and magnitude of the parameters are put in a function where they may be compared with the costs for existing products and, eventually, for new products. Wierda (1988) shows an example of a cost function:

$$\begin{aligned}&\text{Total costs} = \\ &7335{,}3 - 49{,}7 \times D - 3102{,}2 \times N - 1368{,}3 \times \log(C) - \\ &- 10076{,}6 \times \log(S) + 17045{,}7 \times \log(W - 250)\end{aligned}$$

Where D = Spindle diameter
N = Spindle number
C = Capacity
S = Spindle distance
W = Weight

The functions may be adjusted to specific product classes, but a major disadvantage is the fact that each product class needs new cost functions. Investments in new machines, or any other technical development in the manufacturing, will cause the cost functions to become obsolete (or at least uncertain) and in need of update. It is, however, easier to find the link between detail design decisions and manufacturing costs when comparing to the previously described methods.

Several cost functions for special purposes have been developed, e.g.:

- Die-casting by Dewhurst and Blum (1989)
- Machined parts by Boothroyd and Radovanovic (1989)
- Tool costs for sintered parts Knight (1991)
- Turned parts by Mahmoud and Pugh (1979)

Other cost functions are presented by e.g. Dowlatshahi (1992), French (1990), Dewhurst and Boothroyd (1988) and Creese and Moore (1990).

6.2.5 Cost increase functions

Consider the example given below by Wierda (1988), in which a function for cost estimation is derived for a new product. Since the new product is very similar to the old, only a limited amount of parameters need to be updated for the new cost estimation:

$$C_n = C_b(A_m R^{e(m)} + A_p R^{e(p)} + A_q R^{e(q)} + A_s)$$

Where C_n is the costs of the new design (to be estimated)
C_b is the cost for the basic design
R is the ratio of characteristic parameters, new vs. basic
A_i are coefficients with i=m for material, p and q for two processes and s for setup.
e(i) are exponents

Coefficients and exponents may be calculated using regression analysis (Wierda, 1988).

This method is limited to the assumption that the relations between old and new product will remain constant over a time span. This is necessary in order for the cost function to avoid constant updating and considerable uncertainties. The method is therefore not very useful in detail design decisions since it only gives feedback relative to an old product (which could be good or bad from a manufacturing point of view).

6.2.6 Function costs

This approach considers the costs of a complete function rather than a single part. The method exploits the fact that engineers are functionally oriented, and expresses costs of a product function without detailed product knowledge. This approach, which considers a whole function, minimises the risk of sub-optimisation of specific parts (Wierda, 1988).

Since a function in one product may be compared to a function in another product, the costs could also be compared even if the products are quite different. A survey among the companies participating in the DFAA-project showed that five out of eleven (45 %) companies use this method (often as a complement to other methods).

6.2.7 Relative costs

Relative costs are used when a design team is not interested in absolute costs. A reference part may be compared to other solutions. Relative measures of costs, associated with the different solutions, may guide the design team to the cheapest solution.

6.2.8 Product classification

Products may be classified with the use of a number of characteristic parameters. Costs may then be estimated by classifying new products and comparing them with existing products within the same class (Wierda, 1988). If smaller units, modules, of the product are classified in this way, the method becomes similar to the function cost approach. Hence, the main difference between the two methods is the focus on the product and its functions.

A survey among the companies participating in the DFAA-project showed that six out of eleven companies (54%) use this method (often as a complement to other methods).

6.2.9 Times and rates

One of the more frequently used cost estimation methods is to calculate the time needed for manufacturing and then multiplying these times with machine and labour rates. A survey among the companies participating in the DFAA-project showed that nine out of eleven companies (81 %) use this method (often as a complement to other methods). The advantages of this method are that it is flexible and relatively accurate (Wierda, 1988).

Information about labour and machine times may not only be used for cost estimations, but also for calculating the lead-times in manufacturing and, thereby, indicating how the manufacturing system could be designed. Initially, MTM-systems were used to calculate labour times but today there are several software programs available for this purpose.

As described earlier there are DFA-methods already available that may estimate assembly times from the design of individual parts. This is an appreciated functionality among users and is expected to be part of a DFA method. Hence, the method described in this thesis will include time estimations.

Three methods for time estimations have been used to derive estimated assembly times from detailed design of individual parts. These are:

- The database for manual assembly used in the Boothroyd and Dewhurst DFMA method mentioned earlier (Boothroyd and Dewhurst, 1987).

- MTM (Method Time Measurement) estimations (Karlsson, 1966). The system is used for estimating manual work, in this case assembly.

- SAM (Sequence based Activity and Method analysis) estimations (Wiklund, 1990). SAM is based on MTM, but uses combinations of the movements in MTM (i.e. a high level version of MTM).

The resulting time estimation approach for the DFA2 method is found in the evaluation criterion, at part level, in the appendix. The reason why a DFA-method aimed at automatic assembly still uses estimated manual assembly times is for their importance as a reference frame. Moreover, the estimations of automatic assembly times are dependent on the equipment chosen as well as the configuration of the system. This may render estimated automatic assembly times very uncertain since they must be based on specific equipment and supposed system efficiency, and should therefore be avoided as reference frames.

Note, according to the DFMA method (Boothroyd and Dewhurst, 1987) the ideal manual assembly time for each part is three seconds. This estimation is used in DFA2 where each part is assigned three seconds assembly time. All estimated times in DFA2 are added to these three seconds. Hence, a part with only top scores (nines) will have estimated assembly time of only the three seconds. However, a part that is given the scores three and one in the evaluation will have estimated DFA2 assembly times to add to the three seconds.

In order to find out if the time estimation approach in DFA2 gives similar results to other DFA-methods, one product was analysed using DFA2 and another DFA method. The original bicycle bell in Fig 10 (section 2.3.1) was analysed using the Boothroyd and Dewhurst DFMA method (Boothroyd and Dewhurst, 1987). The method estimated the assembly time to approximately 95 s. The same product was also analysed using the DFA2 method, which estimated the manual assembly time to 89 s. The difference is about 6,5 %. It should, however, be noted that neither of the estimated times are absolutely correct since both are estimations. Therefore, DFA2 only considers the estimated assembly time as a reference time. Naturally, the estimated times may be compared to the actual assembly environment and corrected to match the conditions at a specific company. However, in this thesis a generally applicable version is given.

6.2.10 Activity based cost estimations

Conventional accounting methods measure a number of attributes of a product, e.g. the number of direct labour hours, machine hours or materials cost consumed while manufacturing the product (Cooper, 1990a). Overhead and other costs are typically included via a percentage to the measured costs. Overhead costs are traced to a product since it is assumed that they consume these resources (Cooper, 1990a).

In contrast, activity based cost (ABC) systems are focused on the activities performed to manufacture products. Costs are traced from activities to the products via an evaluation of the product’s consumption of activities (Cooper, 1990a; Cooper, 1990b). The base for ABC is the “cost drivers” that are used for measuring the activities performed (a detailed description of the cost drivers in ABC may be found in Beaujon and Singhal (1990)). ABC acknowledges the fact that products do not directly consume resources; they consume activities (Cooper, 1990a). The use of cost drivers to trace costs is what separates traditional cost accounting from ABC systems, and makes the ABC systems more complex than conventional cost accounting systems.

Traditional accountings systems were developed decades ago when product diversity was low, manufacturing processes were largely driven by direct labour, and information-processing costs were high. Therefore, the traditional accounting systems are not applicable for today’s technologically advanced and globally competitive market (Kaplan, 1989). Cooper (1990a) states that conventional cost accounting systems systematically undercost low volume products and overcost high-volume products.

Kaplan (1989) and Huthwaite (1989) suggest that the use of ABC also encourages better product designs. Asiedu and Gu (1998) claim that if companies expect to develop cost competitive products, ABC should be used for cost analysis during the design phase. Larsson et al (2000) describe a “Value-map” to be used during product design, i.e. a way to estimate costs based on ABC.

Fischer *et al* (1994) combine the ABC system with the Japanese approach to work with target costing during early design phases. Emblemsvåg and Bras (1994) use ABC for LCC purposes when focusing on product retirement.

One of the major drawbacks of using ABC is the effort needed to quantify the cost drivers. Moreover, the costs connected to the cost drivers needs updating or the information will be inaccurate when work procedures changes.

The cost estimation system used in DFA2 must be applicable regardless if the companies estimate costs according to ABC or if they use traditional accounting systems. However, the basic idea of ABC may be exploited for use in DFA2. This will be described in the following section.

6.3 Activity based cost estimations in DFA2

It is not possible to apply ABC to a company through DFA2, but the ideas may be used to create a cost estimation system and maybe influence the company to eventually introduce ABC.

The idea in DFA2 is to support the design team in comparing alternative design solutions by providing a method for cost estimations. Consequently, the goal is not to provide a method for estimating the total product cost, which could be used as a base for pricing. There are more appropriate methods for such an estimate.

Oh and Park (1993) describes a typical conventional way of classifying product costs in Fig 32.

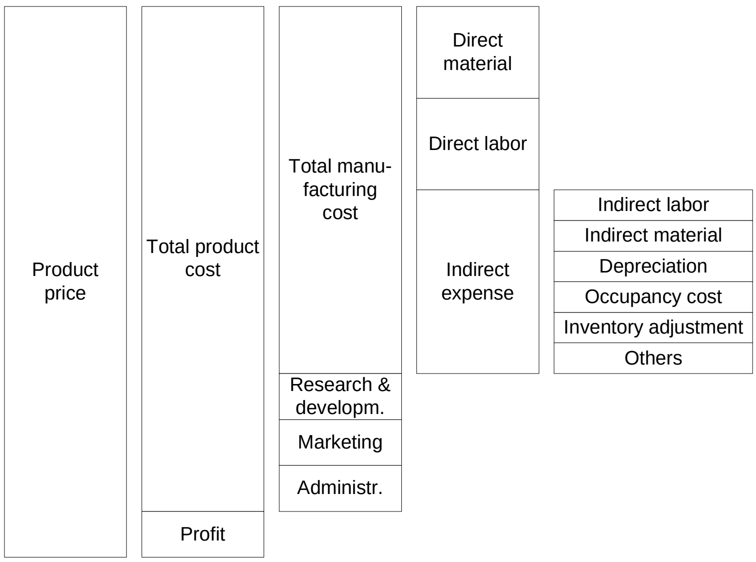


Fig 32: Conventional classification of product cost (Oh and Park, 1993).

In a proposed model for cost evaluation, Oh and Park (1993) states that the manufacturing cost is a major component of the total cost and classifies this cost in four categories; productivity, quality, flexibility and inventory as described in Fig 33.

Total manufacturing cost	Productivity cost	Direct material
		Indirect material
		Direct labor
		Indirect labor
		Machine
		Tool
		Floor space
		Software
	Quality cost	Prevention
		Appraisal
		Int.failure
		Ext. failure
	Flexibility cost	Setup
		Idle
	Inventory cost	Raw material
		WIP
		Finished goods

Fig 33: Reclassification of manufacturing costs as proposed by Oh and Park (1993).

The model proposed by Oh and Park (1993) finally subdivides the cost categories into cost elements, Fig 33, that are assumed to reflect the characteristics of a manufacturing system. The cost elements are similar to the cost drivers used in ABC. A similar approach, based on the ideas of using cost elements, is used in DFA2. The major difference is that the design team use activities and attributes to identify the cost elements.

6.3.1 Activities

In order to compare two alternative design concepts, it must be possible to describe them in similar terms. In order to facilitate the comparison, a number of standard activities have been identified. The design team uses these activities to describe how the two alternative concepts are manufactured, see Fig 34.

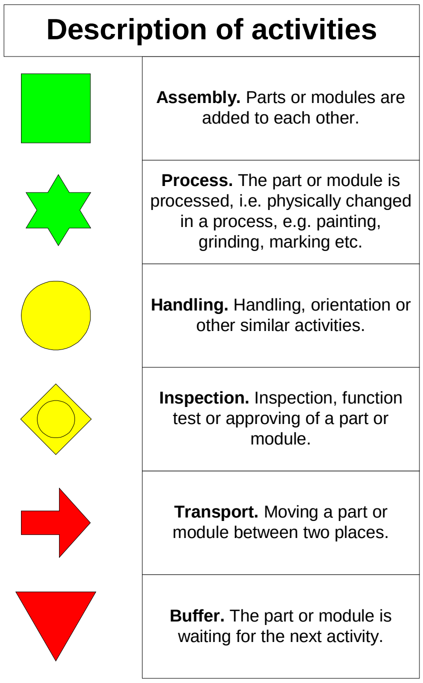


Fig 34: Descriptions and symbols for the standard activities used in DFA2.

The symbols and activities in Fig 34 were chosen together with the companies participating in the DFAA-project. Wiktorsson (2000) use symbols as shown in Fig 35 for classification of activities, in accordance with other models. The symbols for buffer and transport as described in Fig 34 and Fig 35 are similar. However, the symbols for the assembly activity and the handling activity are adapted to the symbols used in the Lucas DFA-method (Leaney and Wittenberg, 1992) described earlier. Finally, the symbols for the process activity and the inspection activity were decided in co-operation with the companies participating in the DFAA-project.

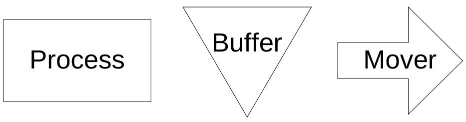


Fig 35: Symbols for activities, according to Wiktorsson (2000).

Initially, the manufacturing activities were described in a generic sequence, but this compromise was not applicable for many products. Therefore, the six activities in Fig 34 were identified as necessary for making a unique description of the manufacturing processes for each part. These activities are considered to be useful for a sufficiently detailed, although not extensive, description of how the parts are manufactured.

It is possible to describe the activities for more than the manufacturing process, but the main aim remains to point out the differences between the two concepts. The way the parts are created forms the selection criteria for the activity to be chosen, Fig 36.

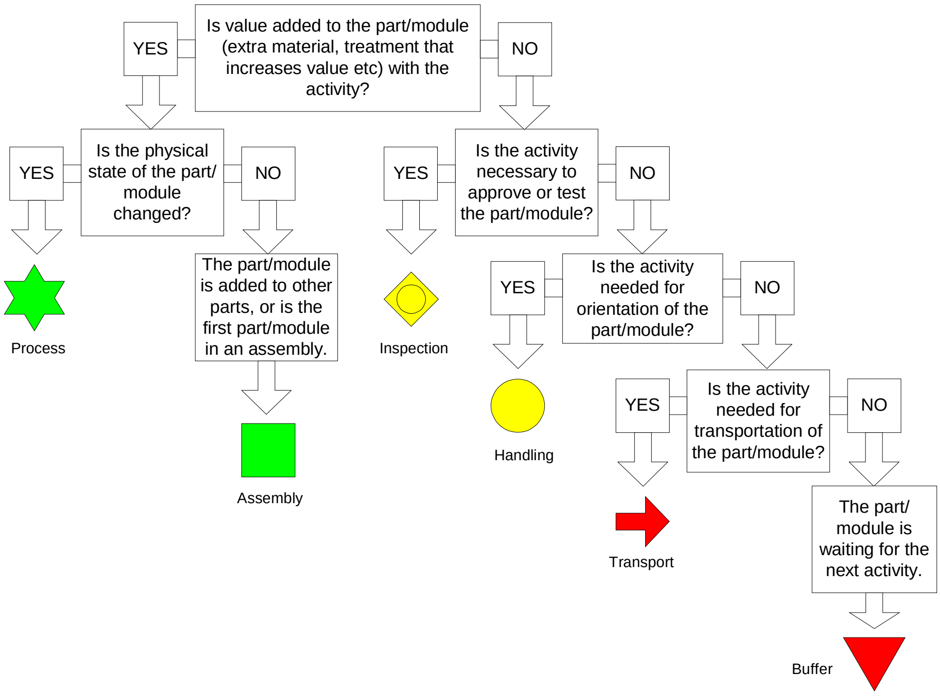


Fig 36: Activity selection flowchart.

6.3.2 Attributes

When the activities to describe the manufacturing process have been identified, the next step is to quantify a number of attributes that describes the activities, Fig 37.

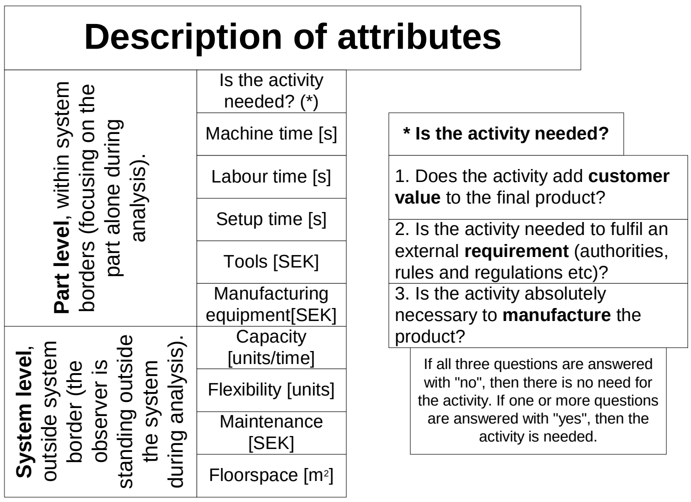


Fig 37: Attributes that describe the activities.

Each activity is described by the same attributes. The attributes were chosen in co-operation with the companies participating in the DFAA-project. It is possible to add company specific attributes to those suggested in Fig 37. During analysis, the attributes are quantified to reveal costs associated to the alternative design suggestions. Naturally, the design team may choose to quantify only a few of the attributes. A definition of each attribute is shown in Fig 38.

Attributes		Definition of the attributes
Part level, within system borders (focusing on the part alone during analysis).	Is the activity needed? (*)	Each activity is questioned in order to always strive for continous improvements.
	Machine time [s]	The machine time needed to perform the activity. (time for completing the activity for one part)
	Labour time [s]	The labour time it takes to perform the activity. (time for completing the activity for one part)
	Setup time [s]	The resetting or set up time it takes to perform the activity.
	Tools [SEK]	Cost for all tools needed that are specific for only the parts being analysed. (total cost for tools needed to complete the activity for one part)
	Manufacturing equipment[SEK]	Investment costs for equipment (that is used for other products or modules) needed to complete the activity, alternatively writing off depreciations.
System level, outside system border (the observer is standing outside the system during analysis).	Capacity [units/time]	The available capacity for this activity (maximum or available).
	Flexibility [units]	Variant flexibility of the activity, maximum level.
	Maintenance [SEK]	Maintenance costs (costs for down-time, labour cost for repairing and for spare parts).
	Floorspace [m^2]	Floorspace occupied by the activity.

Fig 38: Definitions of the attributes used for describing the activities.

During cost analysis it could be possible to use company specific indexes to translate machine- and labour time to the costs comparable to equipment investments, floor space and maintenance. These indexes are not specified in this thesis since they must be company specific.

The analysis results might be calculated for each attribute. For example, this would render an estimation of machine time consumed for one part, total costs for maintenance or where the capacity bottleneck for the process is situated.

As in the assembly analysis, the first step is to question the activity. If a part is not needed, or could be integrated with another part, the need for any activities associated with it is eliminated. Similarly, if an activity could be eliminated, the need for equipment, labour time, floor space and other operations is eliminated. In Fig 39, this is illustrated to show how one part needs a number of activities and each activity needs a number of operations. By the “normal” use of DFA, each part is questioned and if part 1 (P1) in Fig 39 is eliminated, the need for activities A1 to A4 is eliminated, as well as the need for operations O1 to O10. However, if the parts cannot be further reduced, the activity analysis described above may still improve the manufacturing processes since it questions the activities. If activity A1 is eliminated, then the need for operation O1 to O4 is eliminated. Hence, the improvements are taken one step further from a purely assembly based analysis. For example, the activity “assembly” could require operations “gripping” and “insertion”.

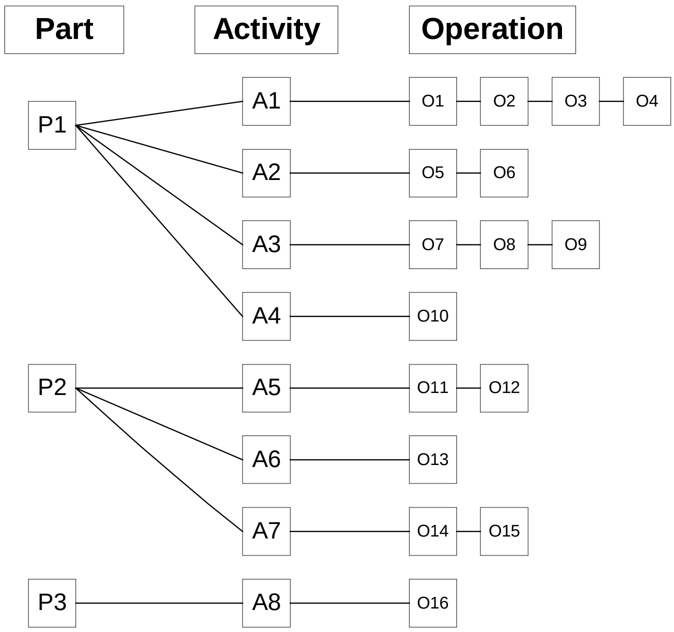


Fig 39: One part requires a number of activities, which in turn requires a number of operations.

This philosophy for improvement is somewhat unique for DFA2 and is considered to take product design and system design one step closer to each other. If the product design team realises (with the support of the activity description in DFA2) that one part requires a lot of activities and operations, it may be easier to motivate redesign of the part.

The description of a product in activities allows the system design to be structured at an early stage. The next step is to describe the equipment needed for each activity. Hence, product designers and system designers are provided with a method that connects their two fields of expertise.

6.3.3 Additional parameters

Additional sets of parameters are used to quantify those properties of the process that are not depending on the activities or could be used to enlighten certain aspects, Fig 40.

Parameters
Supposed manufacturing volumes
Number of parts in the product
Materials cost
Development costs
Item cost
Variant cost
Costs for rejected parts
Guarantee costs

Fig 40: Parameters independent of the activities.

The definitions of the parameters are (units are not specified here and may be chosen to suit each company):

- Supposed manufacturing volumes:
  For visualising the number of times the activity might be requested for this product.
- Number of parts in the product:
  For quantifying if the analysed part is used more than once in the product.
- Materials cost:
  For quantifying the materials cost of the part.
- Development costs:
  For quantifying the development costs, i.e. engineering hours.
- Item cost:
  For quantifying the costs for maintaining a part number (item) in the company.
- Variant costs:
  For quantifying any additional costs for maintaining a part variant.

- Costs for rejected parts:
  For quantifying any costs for rejection of the parts due to poor quality.
- Guarantee costs:
  For quantifying guarantee costs that might occur if part quality does not fulfil customer requirements.

These parameters are subject for company specific adjustments since new parameters could be added and the suggested ones could be altered.

Finally, all this information may be collected on one data sheet (per part or module) for quantification and comparison between different product design suggestions see Fig 41 (the sheet is also available in Appendix A5).

Part/module/product	

Supposed manu-facturing volumes	
Number of parts in the product	
Materials cost	
Development costs	
Item cost	
Variant cost	
Cassation	
Costs for rejected parts	
Other	

Part level, within system borders (focusing on the part alone during analysis).	Description						
	Is the activity needed? (*)						
	Machine time [S]						
	Labour time [S]						
	Setup time [S]						
	Tools [SEK]						
	Manufacturing equipment[SEK]						
	Comment						
System level, outside system border (the observer is standing outside the system during analysis).	Capacity [units/time]						
	Flexibility [units]						
	Maintenance [SEK]						
	Floorspace [M2]						
	Comment						

*** Is the activity needed?**
1. Does the activity add **customer value** to the final product?
2. Is the activity needed to fulfil an external **requirement** (authorities, rules and regulations etc)?
3. Is the activity absolutely necessary to **manufacture** the product?
If all three questions are answered with "no", then there is no need for the activity. If one or more questions are answered with "yes", then the activity is needed.

Fig 41: Data sheet for cost analysis.

6.3.4 Comparing product concept costs

By describing the activities for both (or all) alternative product concepts, and then quantifying the attributes, the design team may have a better understanding of the costs associated with the chosen design. The design team may:

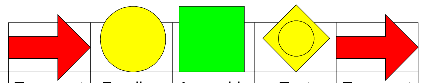
1. Stop the comparison after determining the activities or
2. They may quantify some of the attributes or
3. They may quantify all of the attributes.

The cost information was found to be an appreciated source of information during the design sessions carried out with the DFA2 method in different companies. Due to the nature of this information it is classified and no results from any of the six industrial tests of the cost analysis may be shown here, but an example may be given. Consider the bicycle bell described earlier in Fig 10. If a design team were to quantify why the bicycle bell with three parts was more cost effective than the original design with ten parts, the following cost analysis information could be used. The base object (used for attaching the bell to the handle bar and for upholding the bell) in the re-designed bicycle bell could be quantified as described in Fig 42. This must be compared to a cost analysis for all the individual parts corresponding to the integrated base object. Preferably, each attribute is summarised for comparison with the alternative concept. The costs for a specific activity may possibly be calculated, but requires different units to be translated into one.

Part/module/product	Example

Supposed manu-facturing volumes	200 000 p/y
Number of parts in the product	1
Materials cost	25 SEK
Development costs	
Item cost	
Variant cost	
Cassation	14 SEK
Costs for rejected parts	5 SEK
Other	

*** Is the activity needed?**
1. Does the activity add **customer value** to the final product?
2. Is the activity needed to fulfil an external **requirement** (authorities, rules and regulations etc)?
3. Is the activity absolutely necessary to **manufacture** the product?
If all three questions are answered with "no", then there is no need for the activity. If one or more questions are answered with "yes", then the activity is needed.



Part level, within system borders (focusing on the part alone during analysis).	Description	Transport	Feeding	Assembly	Test	Transport
	Is the activity needed? (*)	NO	NO	YES	YES	NO
	Machine time [S]		8	6	8	
	Labour time [S]	30	3	0		30
	Setup time [S]			4		
	Tools [SEK]		100 000	20 000	73 000	
	Manufacturing equipment[SEK]	15 000	20 000	700 000		15 000
	Comment					
System level, outside system border (the observer is standing outside the system during analysis).	Capacity [units/time]		20 p/min	10 p/min	10 p/min	
	Flexibility [units]		1	100	1	
	Maintenance [SEK]		15 000	20 000	18 000	
	Floorspace [M_2]		1,5	6		
	Comment					

Fig 42: Example of quantified costs for a product concept.

As shown in the case described previously, the initial investigations supported with economic estimations are difficult to ignore and will thereby force the more assembly- and cost effective design alternative to be suggested for the final design.

7 Discussion

7.1 Product design and assembly equipment

The design of a product determines what assembly process that may be used, and, in turn, the assembly process prescribes the assembly equipment, Fig 43. Hence, if the product is designed without this knowledge there is a risk that the company invests in unsatisfactory assembly equipment.

The choice of assembly equipment constrains the assembly process and in turn also limits the product design, Fig 43. This is what is usually discovered if a test batch of a product is manufactured (in case DFA is not used).

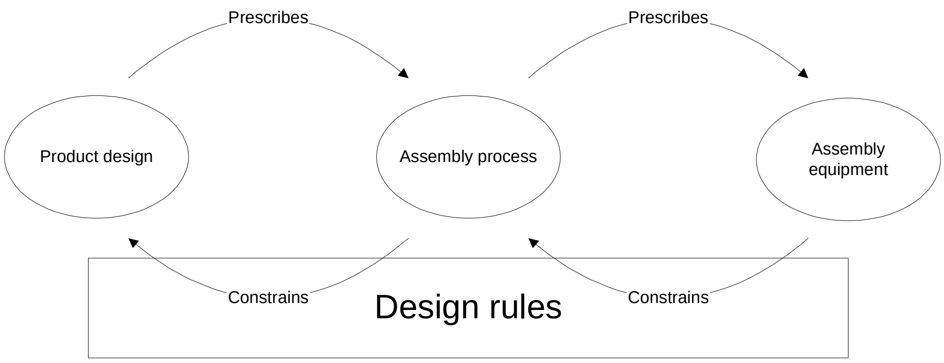


Fig 43: Product design determines assembly equipment, which in turn limits the product design.

In a company where DFA is not used, a typical development of a product could be as described:

1. The design department develops a new product.
2. The manufacturing engineering department builds an assembly system. This system is, in reality, only a prototype.
3. A test batch is assembled.
4. Several problems with the assembly system are discovered and lead to design changes in the product as well as in the system.
5. The re-designed product is assembled in the re-designed assembly system. This cycle may be re-iterated due to new, unforeseen incompatibilities.

Since there may be a couple of iterations between step tree and four as described above, this way of working is to be avoided.

The purpose of DFA2 is to eliminate step three and four, or at least minimise the number of iterations. Since DFA2 contains information on how assembly equipment and assembly processes constrains the product design (in the shape of design rules), it may be used to design the product according to these constrains the first time. This is, in itself, a major breakthrough.

7.2 DFA2 develops within a company

Suppose that DFA2 is put to use in a company and that the design team consists of people from the design department, manufacturing engineering department, purchasing, logistics, quality etc. Then there is a fair chance for that company to continue developing DFA2 and tailor the method to the specific company needs. In the basic shape presented in this thesis, DFA2 is developed to be as general as possible, thereby fulfilling the needs of many companies. When a company starts working with DFA2 it is likely that the number of design rules will increase. DFA2 is then going to be further adapted to the specific conditions at the company using it, Fig 44.

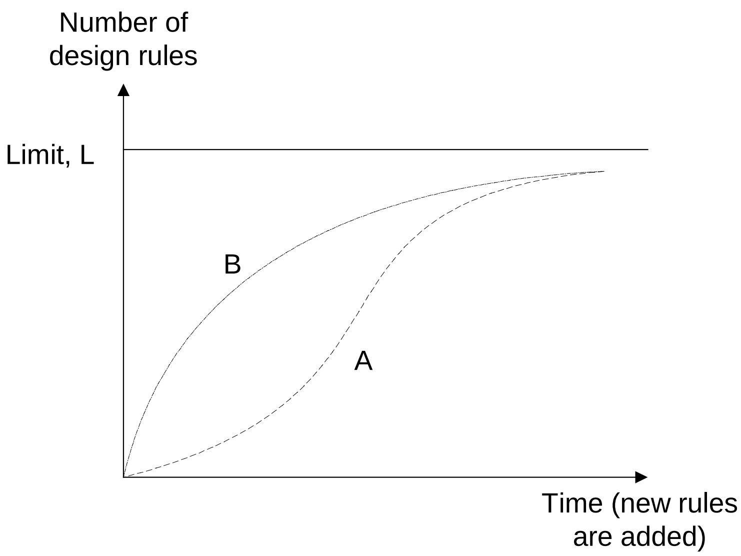


Fig 44: New design rules are added to DFA2 (both curves represents when DFA2 is used in a new assembly system), specific for the company where it is used.

How new design rules are added depends on the company. Experiences from developing a product may be recorded as design rules for the next design team to avoid repeating any mistake. At first, it is likely that the design team is a little careful and will probably add new design rules according to curve A in Fig 44. As the design team becomes more familiar with DFA2, the next project (in a new assembly system and with new products) will probably result in new design rules being added according to curve B in Fig 44. The upper boundary, L, in Fig 44 will exist because time will limit the possibilities to add new rules as well as the assembly equipment not being able to contain unlimited amounts of design rules.

Ultimately, it all comes down to how new ideas are welcomed within a company. The use of DFA2 is dependant on how the design team welcomes these thoughts. During the tests in Swedish companies, DFA2 was met with two attitudes (besides no reaction at all):

- Resistance. A method like this may be considered to question the skills of the product designers. However, the few times this attitude was displayed it was limited to a couple of individuals.

- Appreciation. "Finally a method that we may use to communicate demands from product design and system design". Product designers were satisfied by the fact that DFA2 may show them how products could be designed, something they otherwise had to do by "gut-feeling". System designers felt that they can communicate their needs directly to product designers, rather than showing how impossible it is to assemble the test batch.

7.3 Process driven product design

A possible drawback (or possible advantage, depending on the company strategy) with DFA2 is that it may become, in time, very process oriented. Let us assume that the assembly processes and assembly equipment is somewhat similar during manufacturing of a number of new products. Assume also that the design team adds new design rules continuously when working with DFA2. After some time, the general applicability of these design rules tends to decrease. The design rules will become more and more specific for the assembly system the products are designed for. Eventually, there is a limit that indicates that the design rules are almost only applicable for the assembly system in question and DFA2 is developed to a process driven product design method, Fig 45.

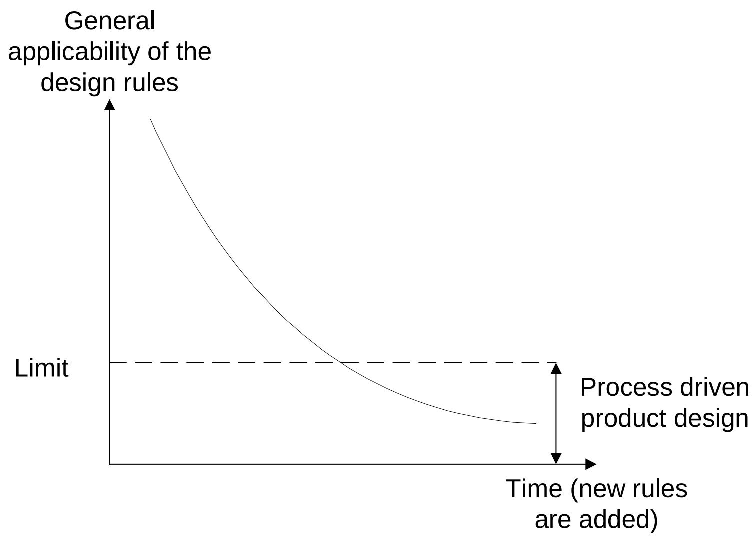


Fig 45: DFA2 could be developed to support process driven product design.

The Sony DAC method (Yamagiwa, 1988), as described earlier, is an example of a method for process driven product design. DAC is closely connected to the Sony Smart Cell assembly system. Hence, DFA2 could be developed to contain similar design rules as DAC, but also be developed to support other assembly systems. This type of assembly system support must be carefully evaluated since the limits posed by an assembly system solution may, in time, decrease the technological evolution of products. Hence, there are hazards in pushing the limits for standardisation of the assembly system too far.

7.4 DFA2 supports Concurrent Engineering

As discussed in section 6, DFA2 may be used to bring product design and manufacturing system design closer together. During tests, DFA2 was considered to be an effective method for communicating the demands from both product design and system design, Fig 46. Since DFA2 is used early in the product development phases, a lot of information is made available, such that system designers may start their work earlier than usual.

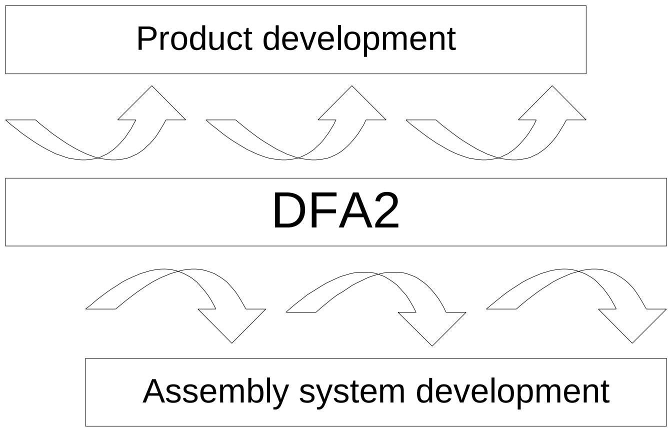


Fig 46: DFA2 may communicate demands from both product and system design as described by one of the companies where the method was tested.

Furthermore, system design may use DFA2 to describe the possible problems in system design and easily suggest changes in product design to eliminate these problems.

It was discovered while testing the method together with the companies that during concept development phases of product design, the product level of DFA2 was useful as a first indication of the product structure (modularisation and related aspects). Later in the design phase, the more detailed DFA2 analyses were conducted when the product had been designed in greater details.

DFA2 was also used to identify why certain assembly equipment did not contribute to system availability as it was supposed to. The parts in a product were analysed with DFA2 and the result was made obvious. The part with the lowest score according to DFA2 (45 %) was the part that caused the assembly equipment to stop. It was thereby possible to identify exactly why this part caused so many problems by analysing the results.

7.5 Objective analysis

When a company was educated in Boothroyd & Dewhurst DFMA during the tests of DFA2 an interesting result was discovered. One of the drawbacks from the use of DFMA is that it is possible to manipulate the results by subjective evaluation.

The people being taught DFA in a company were divided into five groups. All groups evaluated the bicycle bell in Fig 10. The purpose was to induce them to question the parts and finally design the improved bicycle bell themselves (also in Fig 10). During this analysis the Boothroyd and Dewhurst DFMA (Boothroyd and Dewhurst, 1987) procedure for manual assembly was used. Interestingly enough, the five groups produced five very different results, with indices ranging from about 10% up to about 42%. This indicates that a design team may manipulate the results if the goal is to meet a certain percentage. Naturally, the final percentage is not the most important result, but it may indicate that product design improvements may be very different from design team to design team.

Later, the same design teams were introduced to DFA2. Their task this time was to analyse the same bicycle bell as before. This time, the results ranged between 70% up to 73%. This indicates (in resemblance with experiences from tests at other companies) that DFA2 does not allow as much subjective manipulation of the results as with other DFA-methods. Consequently, a result from a DFA2 analysis is likely to be rather similar independent of the members in design team. However, this result is based on only one case and must therefore not be considered as completely verified or valid. For example, the design teams had learned DFA when they started using DFA2, which means that it is possible that this knowledge in itself, not DFA2, made the results more similar.

7.6 Time consumption

When comparing the time consumed to analyse the assembly of a product with the Boothroyd & Dewhurst DFMA method and DFA2 it is important to remember a couple of aspects. It takes longer to analyse a product using DFA2 compared to DFMA. However, to assemble a product automatically is more difficult than manually and therefore it is only natural that such an analysis is more extensive. Furthermore, the result from working with DFA2 is more qualitative (depending on the different evaluation criterion and their three levels) than from DFMA and may be used for redesigning the product.

The time consumed to estimate the costs connected to a product concept depend on how many attributes that is quantified and if the data is easily available. There is no other DFA-method that supports a similar approach, making a comparison regarding time consumption during analysis difficult.

7.7 Software

In parallel to the development of DFA2, there has also been development of demonstration software. The use of DFA2 will be simplified if all the information is available in, and the results gathered in, computer environment. Other benefits of software, like clearness and general view of all information, are simplified.

One of the requirements on a DFA-method described earlier was that the method should be available as software. A snapshot from a demonstration software version is shown in Fig 47.

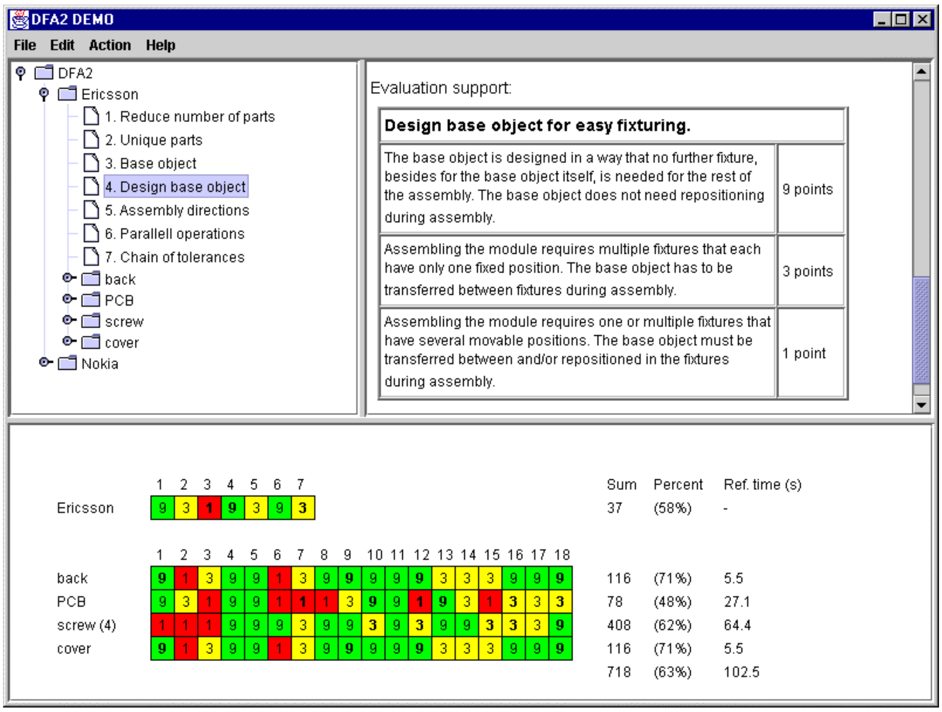


Fig 47: An example of DFA2 as demonstration software.

Another advantage with DFA2 as a software tool is that the results from evaluations may be made clearer with the use of colours. This means that the score from an evaluation 1, 3 or 9 may be interpreted to red, yellow and green.

7.8 Prioritising evaluation questions

A common question is whether it is possible to prioritise among the many questions of DFA2 or not. In other words, the users wonder whether it is possible to say that one question could result in greater savings than another and thereby should be the first aspect to attend to. A short answer is “no”, and this will be further explained below.

In spite of the product design prescribing the assembly process and eventually also the assembly equipment, there are a lot of possible system solutions for each product. The chosen system design depends on manufacturing volumes, batch size, number of product variants etc. Naturally, costs for feeders could be compared with costs for grippers or fixtures and DFA2 could recommend the design team to start redesigning those features that influence the most costly solution. However, in such case, DFA2 must assume that certain solutions are always chosen.

Consider a company that uses DFA2 when designing their new product, but decides to have a manual assembly system. In this case, the fixtures and tools will probably be most costly. In the case of an automatic assembly system, the feeders are more likely to consume more investments. As an example, the question about orientation, and how parts are presented to the system will therefore be viewed differently. In the case of manual assembly, this aspect is of lower interest from an investment point of view, but could eliminate expensive feeding solutions if taken into considerations in an automatic assembly system.

Therefore, there is no recommendation that says that evaluation results from DFA2 should be attended to in a certain order. However, this could be subject for future work.

In general terms, the evaluation results should be attended to according to the resources available and what results the new solutions may show. The points from the evaluation is another way of prioritising the redesign work, saying that all score “1” should be attended to first and all scores “3” after that. As a final suggestion, the activity based cost analysis may reveal what parts that consume a lot of activities and therefore need primary attention.

8 Critical review and future research

8.1 Critical review of the thesis

The critical review of this thesis will first focus on the posed research question and then compare DFA2 to requirements found in the literature.

8.1.1 Research question compared to the results

In section 4, the research question was described as:

"*How can a method for use in early product development, that focuses design for automatic assembly and includes both product evaluation and cost estimation, be structured and what information should it contain?*"

Has this thesis presented enough to answer this research question?

In section 1, seven requirements on a support method for product design was described by Norell (1992):

1 Be easy to learn, understand and use.
2 Contain accepted, non-trivial knowledge within the area it is used.
3 Support the users to find the weak areas in the product.
4 Be a common platform to create a common language for several different professions.
5 Support teamwork and to continually educate and support the users.
6 Contribute to a structured way of working.
7 Provide measurable effects from the development work.

The DFA2 method has been proved easy to learn, understand and use through extensive tests conducted in the companies participating in the DFAA-project. The design rules are accepted knowledge, and for use in automatic assembly it is not trivial knowledge.

The evaluation criteria are used to identify the weak areas in the product. Combining qualitative evaluation with design rules covering a wide set of assembly perspective makes DFA2 well suited as a platform for providing a common language for different professions. The information in DFA2 covers such a broad assembly perspective that a single engineer is not likely to answer all the questions. DFA2 requires a design team with members from different professions to fully avoid the known assembly problems. The design rules in DFA2 will continually educate and support the users as long as they do not know all the design rules by heart.

DFA2 ensures a structured way of working (which in itself is one of the major contributions from this method). Nonetheless, the method allows and recommends iterations to take place. By working as suggested by DFA2, the user cannot overlook important issues to consider, regarding automatic assembly. The evaluation criteria will provide measurable effects from product development.

In conclusion, DFA2 supports product development in early phases since the use of design rules can be used for design of a first prototype. The focus of the method is automatic assembly, and it is possible to evaluate products by using the method. Finally, the method supports cost evaluation, which has been tested and verified in industrial tests. Hence, the research question is fulfilled.

8.1.2 Review of the research method

Most of the research presented in this thesis is the result of close collaboration between academia and industry. There are both advantages and possible disadvantages with this collaboration:

- By working together with a number of companies, empirics and industrial experience are included in the research results.
- The group of companies participating in the DFAA project represented different types of manufacturers, which ensures that the results are applicable within these industries, e.g.;
    - Consumer products and industrial products.
    - Mechanical products and electronic products.
    - High volume manufacturing and low volume manufacturing.
    - Manual assembly and automatic assembly.
- Industrial interests in DFA2 are mainly focused on the resulting method and not how academic the method is. This could mean that industrial interests are given a lot of (too much?) attention in this thesis. However, academic results that are in demand from industry could not be a drawback. Without the support from industry, DFA2 would probably not have been as useful as it has proven to be.

The results presented in this thesis are tested and verified in industry. Different products were used for the tests, but only two are exemplified in this thesis due to confidentiality. The companies wanted to test DFA2 in existing design projects and not on existing products. The disadvantages are mainly the confidentiality about these products, but the advantages are that DFA2 was proven useful regardless if the assembly system was determined or not.

DFA2 is only compared to one other DFA method (Boothroyd and Dewhurst DFMA) regarding DFA indices and assembly time estimation. Generalising test results from only one case may be dangerous, but could still be used as an indication of the results. Besides, the result from any other DFA method is not a definitive truth because they are also based on estimations and assumptions. Moreover, there were no further situations available where DFA2 could be tested and compared to any other DFA method.

8.1.3 Review of DFA2

The following possible drawbacks in DFA2 have been identified:

- There is always a possibility to add design rules to DFA2. This means that DFA2 does not include every known design rule there is. However, the method constitutes the largest collection of design rules known to the author.
- There is no support for the user to prioritise one design rule over another (e.g. if two design rules are contradictory). This prioritisation can only be supported by iterative use of the method, and by cost analysis of the product.
- There is no definitive way of knowing if the structure of DFA2 is the best one or even a correct one. The industrial tests of the method have shown that the structure is very useful, but it is still difficult to determine if it is better than any other structure.
- The limits of the evaluation criteria are of general nature, chosen on the basis of other researchers (presented in section 3) and industrial experience from the group of companies involved in the DFAA project. To establish if an evaluation limit exactly correct is very difficult to determine. In this thesis the scale of evaluation (1, 3, 9) is chosen to fit the measuring system in other established methods. Hence, this thesis has not verified that the limits for a specific evaluation criterion are exactly correct (any new company or manufacturing process may suggest that the limits needs

adjustment). However, this thesis presents a working method that was proven useful in industrial tests.

- The evaluation criterions are not weighted. Suppose that a part in a product is evaluated and rewarded with a ”3” for one criterion. If the same part is rewarded with a ”3” for another criterion, it is not certain that the assembly situations are the same. Two evaluation criterion with the same result can cause different effects on an automatic assembly system. The cost evaluation may help to clarify this problem, as discussed earlier.
- Each evaluation criterion has two or three levels. This research has not evaluated or verified if each level is correct. The proposed limits in DFA2 are established based on academic results and industrial experience. The limits for each evaluation level could be further analysed, but is then subject for future research.
- The cost evaluation may be improved by further developing the activities used in DFA2. Different attributes may also change the economic evaluation result. The attributes may need further development and verification.

DFA2 has fulfilled the research question but some potential drawbacks have been identified. The method is further discussed below and compared according to the requirements stated by other research projects.

8.1.4 DFA2 compared to requirements

The results from the prestudy described earlier were nine requirements on an ”ideal” DFA method (Eskilander and Byron Carlsson, 1998). DFA2 fulfils these requirements see Table 10:

Requirements
Support cross functional teams
Transfer of knowledge
Cost analysis
Quality assurance
Geometric product evaluation
Design suggestions
Software
Prohibit unnecessary variants
User friendly

Table 10: The industrial requirements on a DFA method now fulfilled by DFA2.

Support cross-functional teams

DFA2 discusses many different aspects of developing a product and it is therefore better to have a multi-functional team working with the tool than one design engineer. A good advice when working with DFA2 is to have a team consisting of engineers from at least purchasing department, quality department, design department and manufacturing department. The many different questions raised in DFA2 require skills and knowledge from at least the above-mentioned departments, which was appreciated among the companies.

Transfer of knowledge

Since the basis of the tool is design rules, it can be used as a way of transferring knowledge from one project to the next, from one engineer to the next. Any experience from a project can be added as a new design rule and the tool can grow to be a collection of experiences specific for a company or a system.

Cost analysis

It is possible to analyse the activities required for assembling each part and to quantify a number of attributes connected to these activities. The primary use of the cost analysis is to compare two alternative design solutions, but it is also possible to analyse a complete product.

Quality assurance

A product that is designed according to the rules and evaluation criteria in DFA2 will be better prepared for assembly. A measure of quality in product development could be the number of redesigns. Working with DFA2 will hopefully result in fewer redesigns resulting from early elimination of potential problems in assembling the product. If a design team uses DFA2 during product and system design the result will be a better product and system, which could be considered as quality assured. Companies that tested the method claimed that by using DFA2 the need for re-designs would decrease.

Geometric product evaluation

Evaluating a product with DFA2 will not only give a quantitative it will also show weaknesses in the product and suggest ways for redesign. A DFA2-index can be calculated and give an idea of how well prepared the product is for automatic assembly. The answer is not of the type ”use a SCARA robot to assemble this product”. The result from working with DFA2 is to have a product as simple as possible that enables the simplest automatic assembly process possible. For example, this may be accomplished by adding chamfer to a hole in order to simplify insertion. The companies appreciated the evaluation since DFA2 could be used to explain and pinpoint why the assembly system did not produce as intended. The product was not prepared for automatic assembly, which would be easy to show with an analysis.

Design suggestions

Since the base of DFA2 is the use of design rules, the requirement for providing design suggestions is fulfilled. Qualitative evaluation criteria in combination with design rules provides the user with suggestions for how to design the product to better suit an automatic assembly process. According to the companies that tested DFA2, an evaluation is only half-complete if the design team is not given any suggestions for how to re-design if the solution is not obvious.

Software

Demonstration software of DFA2 do exist, and will hopefully soon be developed to commercially available versions. The software were used for testing DFA2 at the companies with very good results.

Prohibit unnecessary variants

Repeatedly the user is reminded to avoid creating unnecessary variants of both parts and whole modules or products. DFA2 also has evaluation criteria that exclusively evaluate number of unique parts as well as number of parts. Furthermore, the product level in DFA2 raises the horizon for the design team in a way that may help them avoid creating unnecessary variants.

User friendly

To start working with DFA2 does not require several days of introduction. The method was extensively tested in industry in design teams at different companies. Since DFA2 was found useful and easy to use in a large amount of companies, it is likely to assume that it will be useful in other companies as well. Design teams in industry were very fast at learning and making use of DFA2 to their own products.

8.1.5 DFA2 compared to an ”ideal” DFX tool

Huang (1996) identifies three major characteristics for DFX tools:

- Functionality
- Operability
- Focus

Functionality

According to Huang (1996) a DFX tool must fulfil all or some of the following requirements:

- Gather and present facts.
- Measure performance.
- Evaluate whether or not a product/process design is good enough.
- Compare design alternatives: which design is better?
- Highlight strengths and weaknesses.
- Diagnose why an area is strong or weak.
- Provide redesign advice by pointing out directions for improving a design.
- Predict ”what-if” effects.
- Carry out improvements.
- Allow iteration to take place.

Of these requirements, Huang (1996) states that the first five requirements are basic functions that should be included. The second five requirements are more advanced features that not even well known successful DFX tools include.

DFA2 fulfils requirement 1 to 8 and 10. It gathers and presents facts and measures performance. Evaluation is a part of DFA2 and comparison of design alternatives is possible as a consequence of the qualitative evaluation philosophy. Strengths and weaknesses is highlighted and diagnosed in DFA2 and redesign advice is provided. Finally, iteration is allowed to take place.

Requirement eight is fulfilled via the cost analysis in DFA2. To compare two alternative product design solutions could be considered as a ”what-if” prediction. DFA2 does not create the alternative solution, but may be used to compare them regarding assemblability and costs.

Requirement 9 is similar to requirement 7 but more developed. DFA2 is not capable of carrying out improvements by itself. That would require an implementation into a CAD system and that was not within the scope of this research project.

Operability

With operability Huang (1996) means the ease of using the DFX tool to fulfil its functions effectively. Stoll (1988) proposes nine operability criteria for evaluation DFX approaches:

- Pragmatism. Training and/or practise. Concepts and constructs used should already be familiar to the user or easily learnt with little effort.
- Systematic. A systematic procedure ensures that all relevant issues are considered.
- Data requirement and quantitative. Product and process data must easily be collected and presented to the analysis team to enable further actions.
- Teaches good practice. The use of a DFX method teaches good DFX principles and formal reliance on the method may diminish with use.
- Designer effort. The design team, a prime user, should be able to use the DFX tool effectively with little additional time and effort.
- Management effort. Management is not a prime user and therefore effective use of the DFX tool should not be dependant on management support or expectations.
- Implementation cost and effort. It should be distinguished between those changes and commitments that are required for implementing the DFX tool and those changes and commitments that are highlighted by the effective use of the DFX tool for necessary improvements.

- Rapidly effective. Effective use of a DFX tool should produce visible and measurable benefits.
- Stimulates creativity. Effective use of a DFX tool should encourage innovation and creativity, rather than impose restrictions.

Huang (1996) also notes that a sophisticated DFX tool with comprehensive functionality may be too difficult and time-consuming to operate. But on the other hand, an over-simplistic DFX tool may be easy to use, but fail to function effectively.

Criterion 1 is fulfilled since the design teams during the tests felt that DFA2 was a support, not an extra workload. DFA2 is systematic; it follows a generic assembly sequence, and nothing was said to be missing during the tests in industry, which makes criterion 2 fulfilled. Criteria 3 and 5 are fulfilled and the software simplifies the use of the method. Criterion 4 is fulfilled since DFA2 automatically instructs the design team of how to design the products better. Management involvement is always a subject for discussion, but their support or expectations may support the use of DFA2, but is not necessary. The cost and effort of implementation is depending on how many people that needs training and what the software finally will cost. However, training engineers in DFA2 is accomplished fast and easy. The design improvements from using DFA2 are immediate and the method is rapidly effective as criterion 8 states. DFA2 is a way to focus the discussions during design team meetings, thereby stimulating creativity in a very effective way. DFA2 raises several questions that are usually vividly discussed in the team. Hence, all the operability requirements are fulfilled.

<u>Focus requirements</u>

Focus requirements play an essential role in achieving the right balance between functionality and operability (Huang, 1996). Focus is determined, according to Huang (1996), by the following factors:

- Target product sector must be determined, mechanical, electrical, electronic, etc. It would be beneficial to start with a narrow range of products and generalisation could be introduced once sufficient insights have been gained from tests and applications.
- The variable X in Design for X has two parts: X = x + bility. The x part represents one or more processes in the life cycle of a product. The suffix ”-bility” corresponds to the performance metrics. For example ”cost” or ”time” is often used as metrics.

- Design in DFX is concerned with decision-making activities, their outcomes - decisions, and their interrelationships in designing products, processes and systems. Most successful DFX tools are based on interactions between products and processes (activities) with resources implicitly embedded in activities for consideration. This type of DFX tool is called capability-oriented or process-oriented. Alternatively, a DFX tool can be based on interactions between products and resources with activities implicitly embedded in resource centres. This type of DFX tools is called capacity-oriented or facility-oriented.
- It must be determined at which stage of the product design process the DFX tool is to be used. It has been widely acknowledged that the earlier the DFX principle is applied, the greater the benefits, and harder to apply it.
- It should be made clear how the DFX tool is to be used in a design decision-making process. Very few research DFX tools are design systems that actually make design decisions. A few help and guide design decision-making. This type of DFX tool is said to be on-line. Most existing DFX tools are used to evaluate design decisions after they are made. This type of DFX tool is said to be off-line.

DFA2 is primarily aimed at mechanical products. The focus of the tool is on automatic assembly and the ability of the product to be automatically assembled (the name of the method further contributes to imply the focus). DFA2 is process-oriented and supposed to be used as early as in the phase of designing each module in a modular concept. Since DFA2 helps and guides design decisions, it is said to be on-line.

8.2 Concluding remarks

DFA2 has the potential of becoming well accepted within industry, at least since it fulfils many of the requirements stated (as discussed earlier in section 8). There are still areas where DFA2 shows weaknesses (section 8.1.3), but the industrial tests shows that using the method may contribute to designing many excellent products (section 5).

A number of aspects about DFA2 may be concluded:

- By using qualitative evaluation in combination with design rules, the DFA2 method has proven to be usable early in the design stage. The design rules themselves are not new, but in this method a lot of them are collected and ready to use.
- The earlier DFA may be applied, the better results and DFA2 allows analysis and design support for both the whole module (usable in early concept discussions) and for each individual part.
- By being easy to understand, learn and use, hopefully DFA2 may contribute to increasing the use of DFA in industry.
- The focus on automatic assembly is not unique for DFA2, but the approach to analyse according to a generic assembly sequence makes DFA2 easy to apply on manual assembly as well.
- Since the costs for both the product and the assembly system are what decides how the product will be designed in the end, DFA2 may provide valuable information for decisions regarding product development.
- DFA2 may be used for communicating demands from both product design and assembly system design. Difficulties in both product design and system design may be pinpointed and explained with the use of DFA2, which has been proven in the tests.
- DFA2 may be considered a more developed method compared to qualitative DFA methods described in section 3 and an alternative to the quantitative DFA methods described in section 3.
- Finally, DFA2 is special because of the above given reasons (compared to other DFA methods) and finds its place where the other DFA methods does not completely fulfil the demands from the design teams.

Of the companies that were participating in the DFAA-project, several are now in the phase of introducing DFA2 as a tool to be used in all product development projects. Several other companies outside this group are also familiar with DFA2 and have begun to introduce the tool.

As always when it comes to support methods, the method is not better than the people using it. DFA2 is supposed to be a support in the process of developing a new product and its manufacturing system. Minor adjustments to make DFA2 fit a specific company may be needed in some cases, but if it is used as intended this method has proven useful.

8.3 Future work

Naturally, there are some drawbacks in DFA2 as presented in this thesis, and most of these drawbacks may be subject for future research. There are a number of possibilities for developing DFA2 further, e.g.:

1. The time estimation system could be developed to support certain assembly equipment. In this way, DFA2 could estimate assembly times specific for a certain system configuration.

2. Cost analysis could be closer linked to an ABC accounting system in companies, to provide more accurate and faster cost analysis results. The standard activities in DFA2 may be supplemented or exchanged with cost drivers in the ABC system.

3. The design rules could be interpreted and transferred to a CAD system, where design suggestions could support the designers.

4. Since the cost analysis begins with an activity analysis and the step from activities to assembly equipment is not far, a possible development is to go further into system design. If all activities for manufacturing a product are determined, it is a good start in designing the manufacturing system. By starting with the activities, the system designers are not allowed to immediately discuss technical solutions, but rather assembly principles. This could result in more effective assembly system.

5. Automatic assembly is not the only focus for a design team. DFA2 could be developed to include other areas of expertise as well, e.g. machining, testing, recycling, environmental loads etc. But the tool must not become too large or it will be to complicated and demeaning to work with.

When DFA2 is used as a framework for further understanding the connections between product design and automatic assembly system design it was proven useful in industrial tests. When the method was used in the context it was developed for, as a support for product design aimed at automatic assembly, it enhanced the understanding of how a product interacts with its system.

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Appendix: The DFA2 method

This section details the DFA2 method. All references to this appendix are available in section 9.

A short introduction:
DFA2 consists of two parts, product level and part level, Fig 48. It is suggested that the method is first used to analyse (or design) a product at product level, thereafter each part at part level. Each section in the method corresponds to an evaluation criterion and its design rules. The evaluation results are noted on data sheets (available in section A.3 and forward). Since the method, in this shape, is of a general nature, the levels of each evaluation criterion may not fit every company or every manufacturing process. The most important advantage with DFA2 is the structured working approach rather than establishing exactly correct levels for the evaluation criterion.

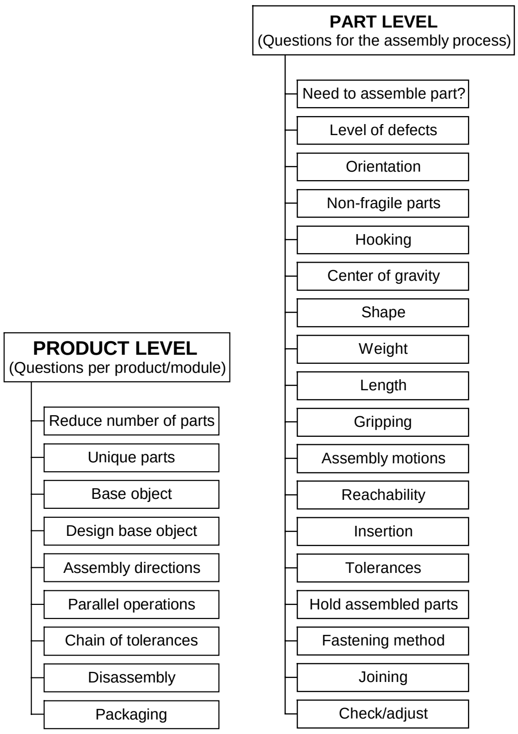


Fig 48: Overview of DFA2.

A.1 Section 1, Product level

The first section of DFA2 deals with questions or design rules for the entire object, module or product, see Fig 49.

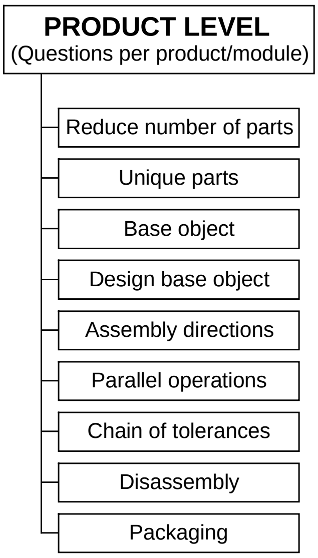


Fig 49: Overview of structure in section 1 of DFA2.

The main goal is to design a product that is as simple (non-complex) as possible, which, in turn, means that the simplest possible assembly process can be used.

By modularising a product, standard modules can be combined to a final product. Modularisation enables opportunity for controlling the number of product variants and to create a modular production system. Identical modules, parts and components might be used in more than one product family. Different product families may result in having the same base material or operations sequence, which can be used when designing a new product or production system (Hallgren *et al*, 1992).

For example, the car industry works with ”platforms” as a way of rendering product families more alike. All the common modules in a number of car variants herewith represent a platform. The platform in a Volvo and a Mitsubishi are the same, i.e. they have several common modules. By working in this manner, products are forced into a kind of standardisation. This standardisation can also facilitate manufacturing, since fewer variants need to be produced and any new product does not have to cause a new or completely rebuilt manufacturing system (Andreasen and Ahm 1986).

A.1.1 Reducing the number of parts

It is very important to reduce the number of parts (both number of variants and total number of parts) in a product (e.g. by standardisation of parts) without changing its functionality (Boothroyd, 1992; Engerstam, 1973; Holbrook *et al*, 1989; Larsson, 1986; Legrain Forsberg, 1988; Norlin, 1970; Pontén *et al*, 1986; Sackett *et al*, 1988). By using integrating production methods (e.g. casting, injection moulding or similar) the number of parts can be reduced, thus facilitating assembly (Andreasen *et al*, 1983; Boothroyd, 1992; Pontén *et al*, 1986).

Reducing the number of fastening elements can be achieved by integration of fastening elements in other parts, e.g. snap fits. Any fastening method should involve few, simple movements to facilitate automatic assembly (Pettersson, 1977). If an extra part is needed, the assembly direction and assembly process should be identical to other parts (Andreasen and Ahm 1986). If the product does not contain any fastening methods like screwing, the possibilities for disassembly, service and maintenance must be evaluated and considered (Norlin, 1970; Sackett *et al*, 1988).

An economic evaluation has to decide whether the cost for developing a special tool for producing an integrated part is higher than the profit of reducing the number of parts (Ulrich *et al*, 1993).

Evaluation support:

Reduce number of parts within each module. Too many parts contribute to large work content within the module.	
Number of parts ≤ 20	9 points
20 < Number of parts ≤30	3 points
Number of parts > 30	1 point

See Fig 50 for a graphical representation of the evaluation criterion.

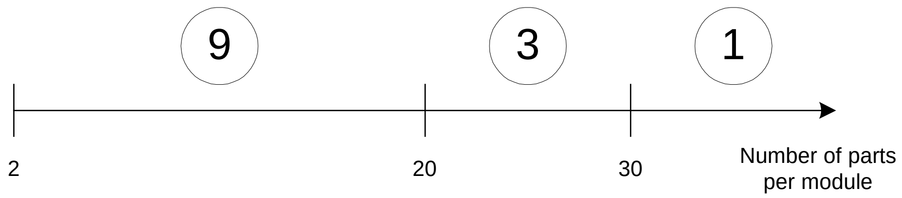


Fig 50: Graphical representation of evaluation criterion for "reducing number of parts".

A.1.2 Unique parts

The strive for using standard parts instead of using only unique parts throughout the whole product family has become common. There are several advantages with using standard parts; i.e. purchases of scale, fewer parts to administrate, and existing equipment can handle all parts etc. However, it is not possible to make an entire product from one type of part, thus it is important to balance the advantages and disadvantages between increasing and reducing number of parts.

Assume that a module among other parts contains five screws. A common approach would be to use the same sort of screw five times instead of five different screws. This could reduce the need for different feeders, grippers and so on.

If no standard parts or already existing parts can be reused, then the approach is to design the new part or component for replacing existing parts or components in different variants of the product (Larsson, 1986). This can lead to several variants being assembled in the same automatic assembly system with no need for new grippers, new fixtures or new feeders.

Evaluation support:

Proportion of unique parts is the ratio

$$\frac{\text{Number of unique parts in the object}}{\text{Total number of parts in the object}}$$

Use only one type of part where it is possible.

Proportion of unique parts < 40 %	9 points
40 % ≤ Proportion of unique parts ≤ 70 %	3 points
Proportion of unique parts >70 %	1 point

See Fig 51 for a graphical representation of the evaluation criterion.

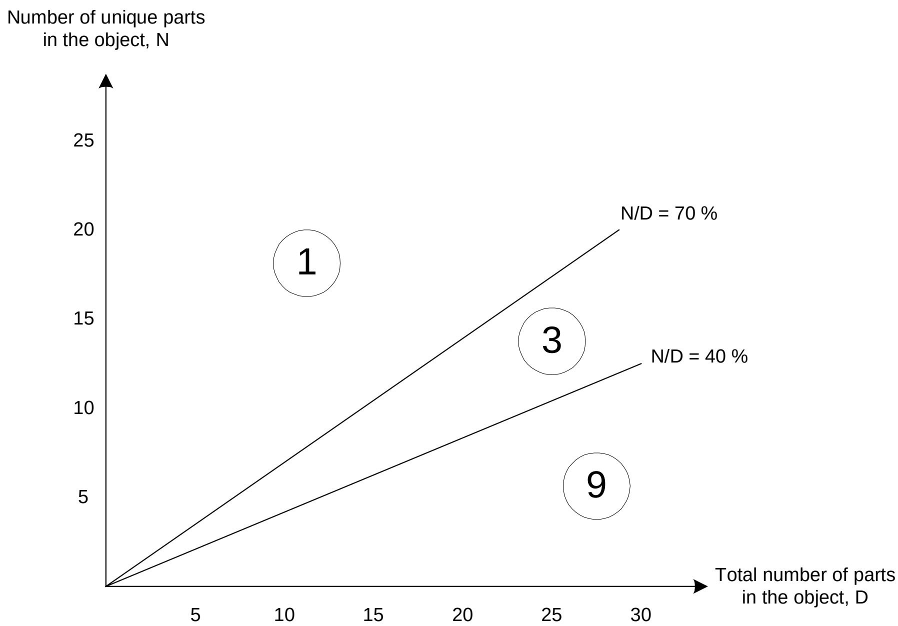


Fig 51: Graphical representation of evaluation criterion "unique parts".

A.1.3 Base object

When assembling automatically it is important to have a base object, i.e. a first part that can be used as a base for the rest of the assembly. The base object can thereby work as a fixture for the rest of the assembly operations and no separate assembly fixtures are needed (Andreasen *et al*, 1983). The base object should have as many assembly surfaces as possible in common with the rest of the components (Andreasen *et al*, 1983).

See, in particular, the section ”design base object”, for design rules on how to design the base object.

Evaluation support:

Base object is a first part that the rest of the assembly can proceed from. All assembly operations are performed on the base object, which leads to simple fixtures and few assembly directions.	
With base object.	9 points
Without base object.	1 point

A.1.4 Design base object

The base object should ideally be designed such that it may be fixed, gripped and transported without loosing its orientation (Andreasen 1988; Boothroyd, 1992; Eriksson, 1983; Pettersson, 1977; Pontén et al, 1986).

Radii and chamfers should be designed such that the base object be easily placed in its fixture. The base object should also be designed to ensure a steady placing in the fixture, see Fig 52. Holes and pegs for guiding the insertion should be conical (Norlin, 1970). A simple contour is ideal, since it facilitates fixturing (Larsson, 1986). The tolerances for the parts should be decided with regards to the base object. If any measure is larger than the tolerance, the assembly system will probably stop (Norlin, 1970).

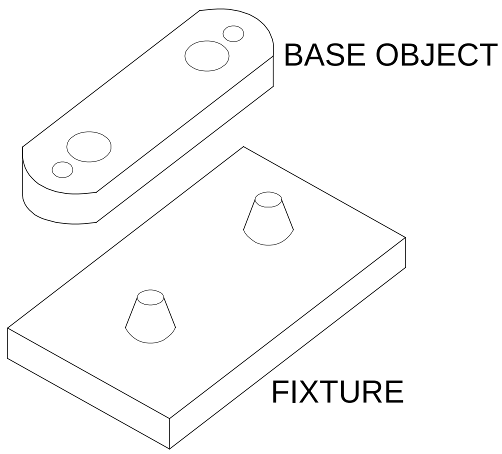


Fig 52: Features, which enables simpler fixturing.

A base object should be designed with a stable centre of gravity considering (Engerstam, 1973):

- Centre of gravity as low as possible.
- Support points as far apart as possible from one another.
- Possible holes for guiding the insertion and/or strapping elements.

Furthermore, the base object should not exhibit a larger number of composition points than what may be simultaneously assembled. The motions required should, ideally, be vertical or horizontal and no flipping or turning the base object should occur during assembly (Andreasen *et al*, 1983). Turning the assembly requires extra equipment. Furthermore, the fixture becomes more complicated since it has to be adjusted to new surfaces for location. There is also a risk that already assembled parts can lose orientation if the assembly is turned (Norlin, 1970).

Evaluation support:

Design base object for easy fixturing.	
The base object is designed in a way that no further fixture, besides for the base object itself, is needed for the rest of the assembly. The base object does not need repositioning during assembly. One assembly direction.	9 points
Assembling the module requires multiple fixtures that each has only one fixed position. The base object has to be reoriented or transferred between fixtures during assembly.	3 points
Assembling the module requires one or multiple fixtures that have several movable positions. The base object must be transferred between and/or repositioned in the fixtures during assembly.	1 point

A.1.5 Assembly directions

The product should be structured to ensure that all assembly operations occur from one direction, preferably from above (also called hamburger assembly, pyramid assembly or sandwich assembly). This assembly direction is preferable since it is easier to assemble parts from this direction and it is also possible to use gravity when inserting and fastening (Engerstam, 1973; Norlin, 1970; Pettersson, 1977).

Evaluation support:

Assembly directions, totally in the whole product/module	
One assembly direction into a fixed base object.	9 points
Two assembly directions into a fixed base object (alternatively one assembly direction in a movable base object with two different fixed positions).	3 points
Three or more assembly directions into a fixed base object (alternatively assembly in a movable base object with several different fixed positions).	1 point

A.1.6 Parallel operations

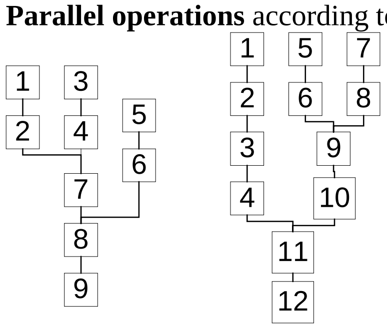
If components can be assembled in parallel, the total lead-time in the assembly shop can be reduced drastically compared to ordinary sequential assembly. A change in any component will result in a significantly limited change in the assembly system if it is being assembled in parallel (Erixon *et al*, 1994).

A parallel assembly process and a standardised set of parts may ensure that all the variants of the product can be produced in the final assembly. This can result in simplified logistics, less work in progress, less storage, less buffers and so on (Andreasen and Ahm 1986; Erixon et al, 1994).

A sub-module or component should not be designed as an emergency solution for an assembly problem. There should be a straight assembly sequence that does not require sub-assemblies, but gives the possibility to assemble in parallel, which in turn can shorten the lead-time.

Evaluation support:

Parallel operations according to the following example:



The assembly sequence to the left has $\frac{7}{9}$ parallel operations;

the sequence to the right has $\frac{10}{12}$ parallel operations.

> 50 % parallel operations	9 points
0 % < parallel operations ≤ 50 %	3 points
No parallel operations.	1 point

See Fig 53 for a graphical representation of the evaluation criterion.

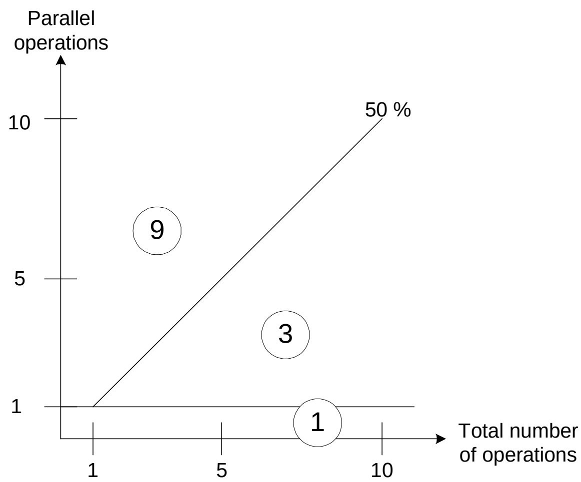


Fig 53: Graphical representation of evaluation criterion for "parallel operations".

A.1.7 Chain of tolerances

When assigning tolerances to a part there is a need for taking into consideration, for example, orientation and insertion of the part. Automatic assembly systems have fixed measures for grippers, fixtures etc., which means that all tolerances must be accordingly adjusted. If any measure is outside these tolerances the assembly system will probably stop (Norlin, 1970). Avoid chains of tolerances; see Fig 54, since it means that a sum of multiple tolerances, which leads to a large risk for having assembly difficulties (Engerstam, 1973; Larsson, 1986).

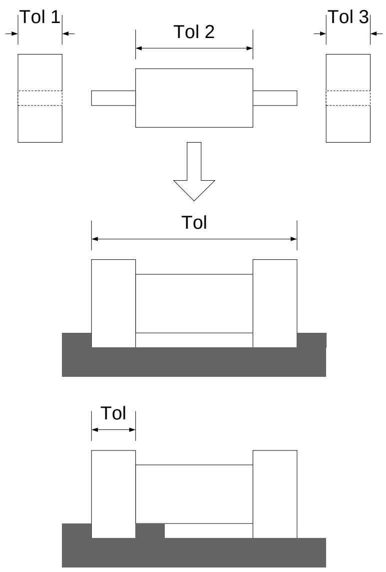


Fig 54: Avoid chains of tolerances.

Evaluation support:

Chains of tolerances should be minimised to have a more reliable assembly process.	
No chains of tolerances significant for the assembly process. Only the tolerance of each individual part is significant.	9 points
There are chains of two tolerances significant for the assembly process in the module.	3 points
There are chains of three or more tolerances significant for the assembly process in the module.	1 point

A.1.8 Disassembly

Few parts and simple fastening methods result in easier, and thereby cheaper, disassembly (Wittenberg, 1992). Snap fits can be disadvantageous for disassembly if they are not designed to simplify disassembly, service and maintenance. Standardisation of fastening elements is important since e.g. fewer types of screws requires fewer types of tools, which simplifies disassembly and service.

Liquids that are hazardous for health or pollution should be avoided (Wittenberg, 1992). Any hazardous substances in a product lead to difficulties in disassembly and re-use of the product.

Valuable parts must be designed to be easily removed (Wittenberg, 1992). These parts can then easily be recycled or re-used in another product.

A large range of materials in a product might cause problems. Use preferably only a few different types of material, which simplifies sorting (e.g. standardisation of plastics) (Wittenberg, 1992).

If a product is easy to disassemble, it will also be easy to adjust (Engerstam, 1973). A product that is easy to disassemble will also be prepared for service. Consider, in this tool, disassembly as ”reversed assembly” for each part and operation according to the same criterion as for normal assembly. This approach entails that for disassembly this tool can be used for all questions at object level and for ”fastening method”, ”joining” and ”fit in” under part level.

Luttropp (1997) divides products into five families:

1 Hamburger design, e.g. mobile phone or toy car. The product has at least two halves that can be separated and then sorted. The joining between the different halves is critical.
2 Shell design, e.g. flashlight, ammunition or electrical toothbrush. The product has a closed shell structure that has to be destroyed before parts can be sorted. Hamburger designs that are glued or welded together are included in this group.
3 Rod design, e.g. screws, pliers or screwdrivers. The product is mostly made of one or several pieces of the same homogenous material and can be sorted immediately.
4 Twin design, e.g. water tap, jewellery, or car wheel. The product has more than one important sorting object on the first sorting level and the loadcase for this first level should be designed with great care. The product is first separated and then sorted.
5 Dressed design, e.g. toaster, computer or car. The product has a carrier on which nearly all parts are mounted and has to be separated before sorting. There is often a lot of empty space inside the product and when designers try to make the product smaller it can often be transformed into a hamburger design.

No evaluation criterions for disassembly were found directly applicable or industrially verified.

A.1.9 Packaging

The product should ideally be packed for transportation to customer in a way that requires a minimum of material and space. If there is a base object, the fixture used during assembly can probably provide suggestions for how to pack the product in a reliable way.

If the customer is going to use the product as a component in his assembly (e.g. products delivered by sub-contractors) process it might be of importance to make sure that the product does not lose orientation during transport. One must ensure that there are surfaces both for packing and un-packing.

No evaluation criterions for packing were found directly applicable or industrially verified.

A.2 Section 2, part level

Section 2 of DFA2 deals with questions and design rules for each part in the product. The questions are as detailed in Fig 55.

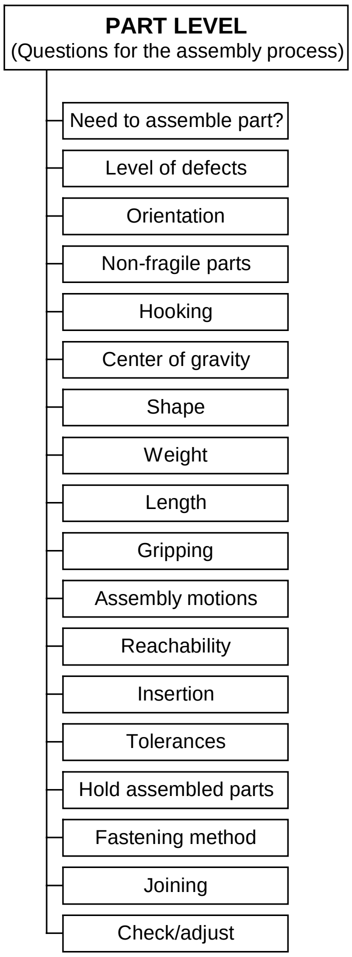


Fig 55: Overview of the structure in section 2 of DFA2.

All the questions are general for any part. The main goal is to design a product that is as simple (non-complex) as possible, but still fulfils the intended functional requirements. This may enable the implementation of the simplest possible assembly process.

NOTE! Time estimations are based on the use of an ideal manual assembly time of three seconds per part (Boothroyd and Dewhurst, 1987). All estimated times in DFA2 are added to these three seconds.

A.2.1 Need to assemble part?

The basic principle is to avoid assembly if possible (Eversheim *et al*, 1982). The aim is to try to integrate parts and thus minimise the number of parts in the product.

According to the Boothroyd & Dewhurst (B&D) method there are three questions for validating the existence of each part in a product (Boothroyd, 1992):

1 Does the part move, relative to other already assembled parts during normal use of the finished product?
2 Does the part have to be of other material than already assembled parts, or isolated from them?
3 Does the part has to be separate from already assembled parts because assembly or disassembly otherwise is impossible?

If any of these questions are answered with a ”yes”, there is an indication that the part needs assembling. If all three questions are answered with ”no” the part has no reason to exist and should be integrated with others or eliminated (Boothroyd, 1992). The first part in an assembly should be a base object and must by definition exist. Thereby, the base object is the target of comparison for part number two regarding question number one and two.

Reasons for parts to be separate might include simplified service and maintenance. There might also be restrictions in the assembly process that does not allow integration of parts (Holbrook *et al*, 1989). It is a good advice to consider benefits and disadvantages in eliminating assembly or increasing variants of parts.

Lin and Hsu, (1995) suggests another approach for part-count reduction as shown in Fig 56. The difference to the approach suggested by Boothroyd (1992) is that Lin and Hsu also include the functionality of the part. This means that each part has to support a function in the product to avoid being eliminated or integrated.

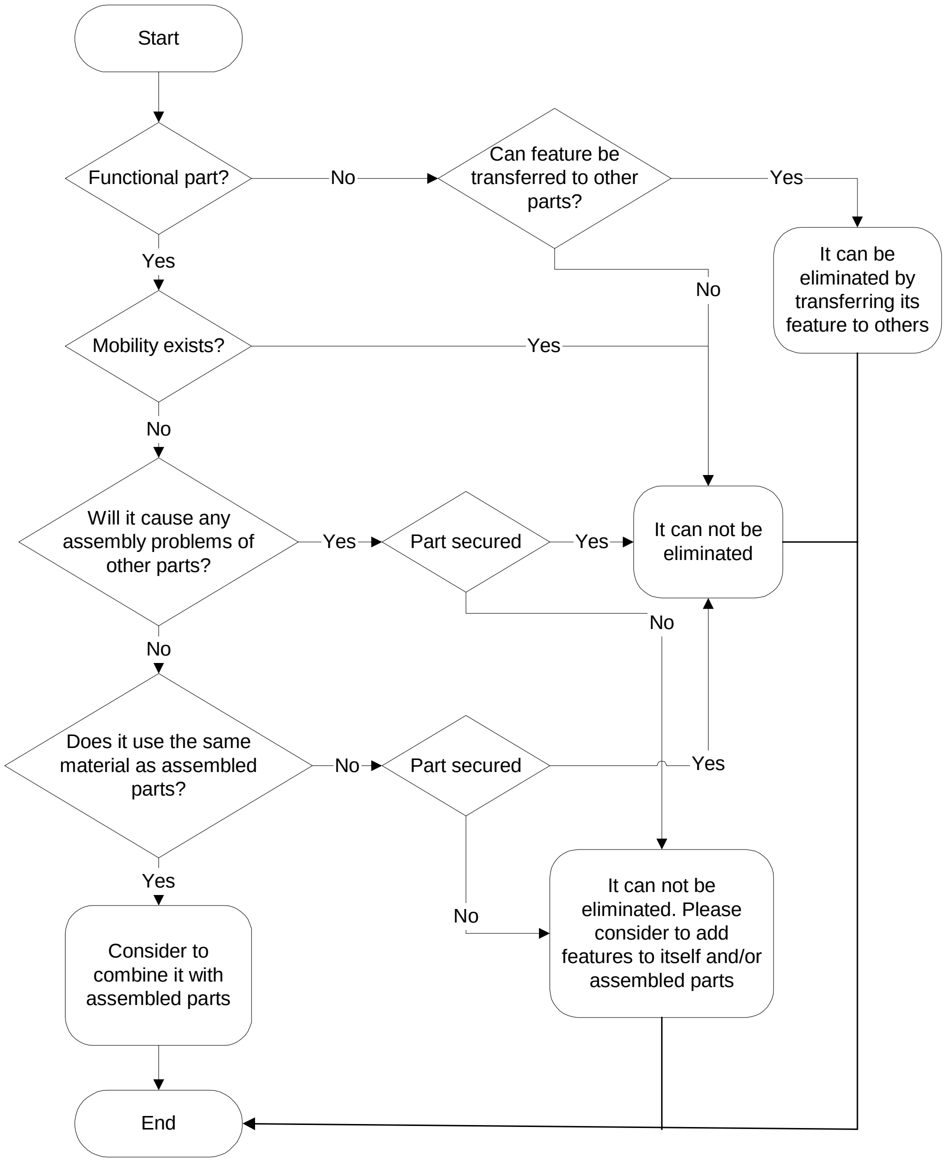


Fig 56: Graphical representation of design rules for eliminating parts (Lin and Hsu, 1995).

Evaluation support:

Need to assemble parts? The questions described above have to be answered for evaluation. A part that does not perform a relative motion has to be of another material or must be separated in order for assembly/disassembly reasons to be eliminated or integrated.	
The part has reasons for being separate (at least one ”yes” to the three questions)	9 points
The part should be eliminated/integrated (all three questions answered with ”no”) but the part is still a separate part in the product.	1 point

A.2.2 Level of defects

Bought standard parts must be reliable enough to eliminate unscheduled stops in an automatic assembly system because of problems in feeders, gripping- or fitting operations. The level of acceptance should be decided by an evaluation of the price of parts with higher quality and costs due to unscheduled stops in the assembly system, (Pettersson, 1977). Parts and components that are produced within the company must also have the same low level of defects.

Acceptable level of defects regarding, e.g. the quality of screws, ought to be at a rate below 0,1 % (less than one defect per 1000 parts) for being suitable for automatic assembly (Langmoen, Ramsli, 1983).

Evaluation support:

Level of defects of parts that are to be assembled. Geometric defects that might cause unscheduled stops in an automatic assembly system should be avoided, or parts with functional defects.	
$P < 0{,}1$ %	9 points
$0{,}1 \% \leq P \leq 1{,}5$ %	3 points
$P > 1{,}5$ %	1 point

See Fig 57 for a graphical representation of the evaluation criterion.

Fig 57: Graphical representation of the evaluation criterion "level of defects".

A.2.3 Orientation

The need for orientation should be minimised (Eversheim *et al*, 1982). When orientation is needed, the parts should be designed for as easy an orientation as possible to ensure high reliability in e.g. feeders. There are several ways of designing for ease of orientation, e.g. using the shape or the centre of gravity of the part (Pontén *et al*, 1986).

One way of eliminating the need for orientation is to have parts delivered oriented. The supplier has the part exactly orientated during the manufacturing process and it is both expensive and time consuming to re-orient a part. If the supplier instead of throwing the part in bulk, places the part in a fixture, a magazine or something similar the orientation can be maintained into the assembly process. For example, the electronics industry used the technique of having parts on tape, i.e. oriented in small boxes in a plastic film with a lid.

Evaluation support:

Orientation. If a part could be delivered oriented, cost and uncertainty in the process would be eliminated.	
No need for re-orientation of the part	9 points
Part is partly orientated, but needs final orientation	3 points
Part orientation needs to be re-created.	1 points

A.2.4 Non-fragile parts

The feeding of parts is often regarded as a problem area. Some say that when the feeders are working, then the whole assembly system is working. Many of these problems are due to the fact that very few parts are designed for automatic feeding. There are many benefits to be gained in designing for easy feeding, identification and for placing in magazines (Ahlbom *et al*, 1982; Arnström *et al*, 1984; Gröndahl *et al*, 1983; Pontén *et al*, 1986; Boothroyd *et al*, 1979).

Feeding should be as simple as possible. The most preferable approach is to include the part fabrication process in the assembly system (e.g. producing springs only when they are needed for assembly) in order to maintain the orientation of the part (Rooks, 1987).

Ideally, one should design the product with as few fasteners as possible, and let variants of the same part have uniform contact surfaces that are used in the assembly process. This can reduce the need for several feeding and assembly units (Larsson, 1986).

Vibratory feeders are widely used as feeding solution, but they require non-fragile parts with centre of gravity and shapes that can be used for such feeding. Too small tolerances can cause the feeders to stop and thereby the rest of the system (Norlin, 1970). Surface tolerances for parts, which an assembly system does not have to consider, should be avoided when possible (Andreasen *et al*, 1983). High friction for a part can be a drawback since e.g. gliding driven by gravity will be difficult (Engerstam, 1973).

Evaluation support:

Feeding often requires **non-fragile parts**	
Part is not fragile	9 points
Part can be scratched, which is not acceptable.	3 points
Parts can not fall without deforming	1 point

A.2.5 Hooking

Parts should be provided with properties that makes it impossible for the parts to nest, tangle or hook into similar parts when storing them in bulk (Boothroyd, 1992; Eversheim *et al*, 1982), see Fig 58. One way of accomplishing this is to avoid projecting shapes and parts with holes, or making the holes very small (Engerstam, 1973; Mohan, 1987).

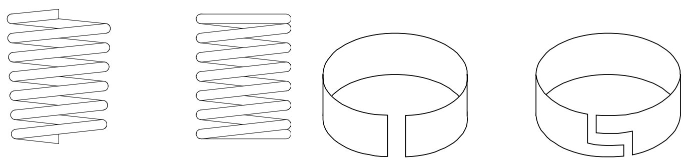


Fig 58: Simple changes may eliminate the risk of parts hooking into each other (Norlin, 1970).

The materials in the part can also have negative effects and it is, for example, a good idea to avoid materials with residual magnetism, sticky materials and so on (Engerstam, 1973).

One effective way to avoid this is to copy the electronics industry, where parts are often fed in tape or ribbons, see Fig 59. This facilitates feeding enormously (Andreasen *et al*, 1983).

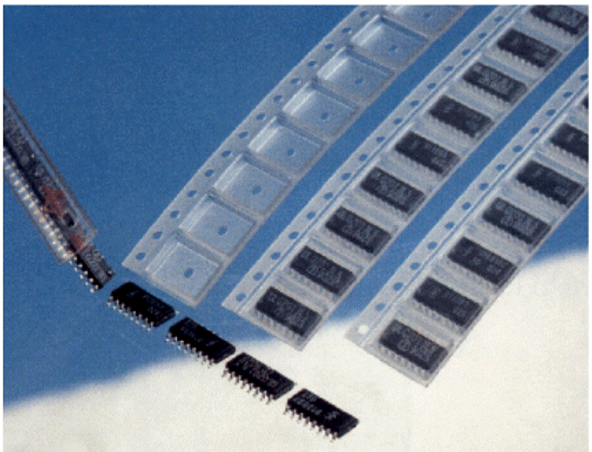


Fig 59: Parts delivered on tape will simplify feeding and orientation.

Evaluation support:

State during feeding, hooking: There should be no risk of parts hooking into each other for example in a bulk vibration feeder.		**Man. ref. time**
Parts cannot hook to each other and tangle up.	9 points	0 s
Parts can hook to each other and tangle up.	1 point	0,7 s

A.2.6 Centre of gravity

The following aspects should be considered regarding the centre of gravity in a part:

- The centre of gravity should give the part a very stable state of rest (Engerstam, 1973)
- The centre of gravity should be very eccentrically or in another special position (Engerstam, 1973).

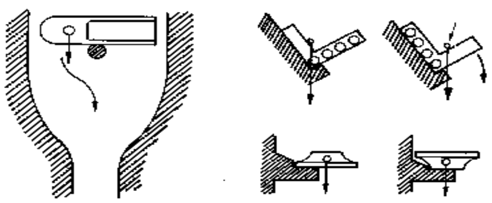


Fig 60: Examples of how centre of gravity can be used for feeding.

Using centre of gravity in feeders is one of the most common ways of separating parts from each other. This is the reason why the assembly process can be significantly simplified if the centre of gravity is placed in a way similar to that illustrated in Fig 60.

Evaluation support:

Centre of gravity for the part should be positioned for use in feeding. Drop the part repeatedly on a table to determine its state of rest. Simple orientation often means reliable and cost effective feeding.	
Part has a stable state of rest and orients itself with correct side upwards.	9 points
Part has a stable state of rest, but orients itself with wrong side upwards.	3 points
Part has an unstable state of rest and orients itself with different sides upwards.	1 point

A.2.7 Shape

To facilitate orientation the following aspects regarding part shape should be considered:

- Shapes that can be used as means for orientation should be placed in the outer contours and preferably well visible (Engerstam, 1973; Eversheim *et al*, 1982).
- Include obstacles for rotation in the contour (Engerstam, 1973).
- Surfaces on the part, e.g. a metal sheet with a bent edge on one side to ensure that the part can be hung (Andreasen *et al*, 1983).
- In cases when parts are going to be identified with a vision system, there is sometimes a need to have surfaces with clear contrasts (Hallgren *et al*, 1992; Pontén *et al*, 1986).

- Symmetrical parts (Andreasen 1988; Pettersson, 1977; Pontén *et al*, 1986), or very asymmetrical (Pontén *et al*, 1986). If a part cannot be symmetrical (which is preferred) it is sometimes better to make it more asymmetrical (Andreasen *et al*, 1983; Boothroyd, 1992; Engerstam, 1973; Holbrook *et al*, 1989; Mohan, 1987; Norlin, 1970; Pontén *et al*, 1986).

The part should have as few vital orientations as possible to simplify orientation. Fig 61 shows an example of how a hole influences the number of vital orientations of a part. To the left, the part has to be oriented not only with one of the sides, but also with one of the edges to find the hole. The next part has the hole in the centre of one side and the probability for orientating the part correctly is 1/6. The two parts to the right are very easy to orient, and the probability for orientating the part correctly is one (Norlin, 1970).

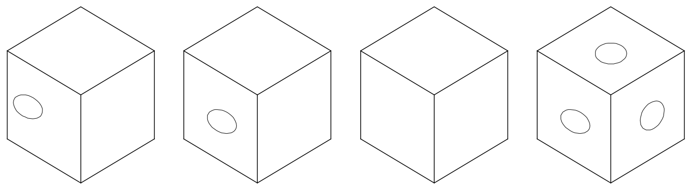


Fig 61: Example of parts with different number of vital orientations (Norlin, 1970).

Smaller asymmetries in a part should not be bigger than 0,1 D (Diameter) or 0,1 L (Length) to simplify orientation in a feeder.

Symmetries can be divided into two classes, α-symmetry and β-symmetry (Boothroyd and Dewhurst, 1987), see Fig 62. The α-symmetry refers to how many degrees the part has to be rotated around one of its ends to regain the same geometrical properties it had in the first position. The β-symmetry refers to how many degrees the part has to be rotated around its axis of insertion to regain the same geometrical properties it had in its first position.

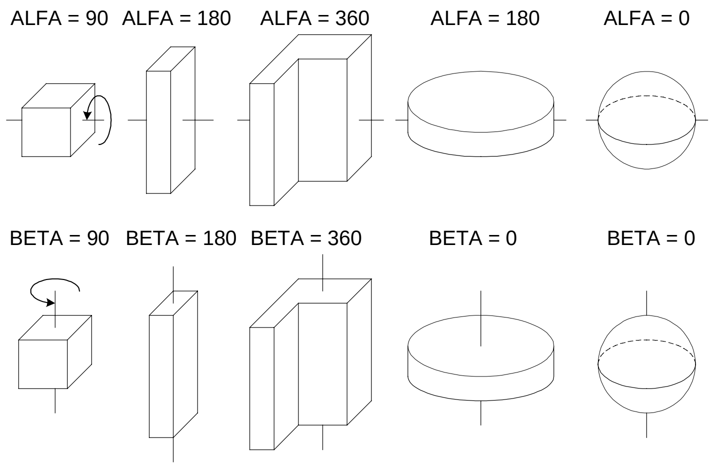


Fig 62: Alfa and beta symmetries for different parts.

Evaluation support:

Shape of a part is the sum of α- and β-symmetry. Symmetrical parts decrease the need for unique orientation.		**Man. ref. time**
$\alpha + \beta < 360$	9 points	0 s
$360 \leq \alpha + \beta < 540$	3 points	0,6 s
$540 \leq \alpha + \beta \leq 720$	1 point	0,9 s

See Fig 63 for a graphical representation of the evaluation criterion.

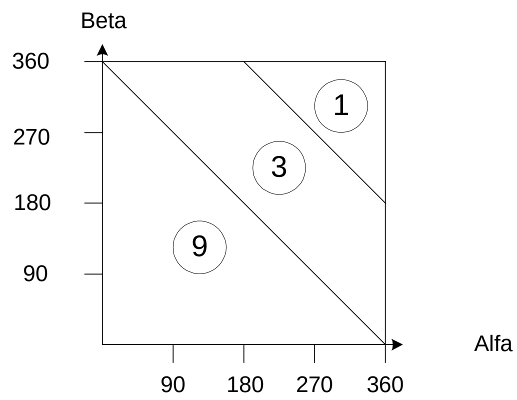


Fig 63: Graphical representation of the evaluation criterion "shape".

A.2.8 Weight

Minimise the weight of the product, since it allows simpler and less expensive assembly equipment (Sackett *et al*, 1988). Since the relation between high precision, fast movements, weight of the part and the price of the assembly equipment are very coupled, it can be wise to avoid heavy parts if possible. Heavy parts mean larger and stiffer equipment and can also mean risk for impact stress, (Engerstam, 1973). Low weight of parts can also mean lower handling- and fitting times, (Holbrook et al, 1989). However, with too low a weight there might be problems with adhesion forces.

Evaluation support:

Weight, of the part. This affects the choice of equipment.		**Man. ref. time**
0,1 g ≤ G ≤ 2 kg	9 points	0 s
0,01 g ≤ G < 0,1 g or 2 kg < G ≤ 6 kg	3 points	1,5 s
G < 0,01 g or G > 6 kg	1 point	3 s

See Fig 64 for a graphical representation of the evaluation criterion.

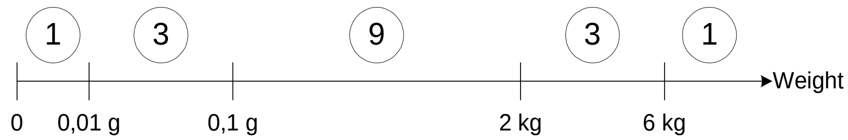


Fig 64: Graphical representation of the evaluation criterion "weight".

A.2.9 Length

The length of a part affects the design of e.g. feeders, grippers, fixtures etc. An assembly cell must also be adjusted to the size of parts going that are to be assembled, whereas long parts might require extra or special equipment.

Evaluation support:

Length. The length of a part is the longest side of an enclosing prism. This affects the choice of equipment.		**Man. ref. time**
5 mm ≤ L ≤ 50 mm	9 points	0 s
2 mm ≤ L < 5 mm or 50 mm < L ≤ 200 mm	3 points	0,7 s
L < 2 mm or L > 200 mm	1 point	1,2 s

See Fig 65 for a graphical representation of the evaluation criterion.

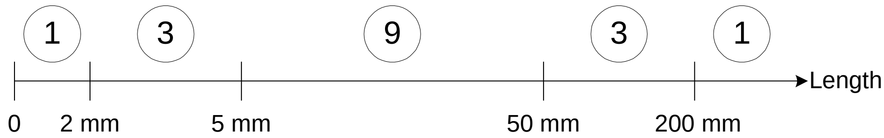


Fig 65: Graphical representation of the evaluation criterion "length".

A.2.10 Gripping

As a general rule, all parts must be easy to grip in automatic assembly since a gripper is less flexible and usually requires more space than the human hand (Hallgren *et al*, 1992; Norlin, 1970). If a part can be assembled with thumb and index finger it can be easy to grip with a mechanical gripper. To resemble the conditions for a robot trying to grip a part, imagine a human assembling with one arm behind the back, blindfolded and the free arm for gripping the part is equipped with a boxing glove.

Grippers are usually relatively expensive since they are often specially made for picking one specific part. If many parts can be gripped with the same gripper it will be economically beneficial. Special surfaces for gripping parts are not always needed, but sometimes necessary in order to avoid multiple grippers (Eversheim *et al*, 1982). The surface for gripping should be possible to use as final positioning of the part when it is gripped. Use different surfaces for gripping and positioning parts in feeders (Hallgren *et al*, 1992).

The outer and inner contours of parts should, ideally, be gripper friendly with defined gripping surfaces. The ability to grip a part increases if the part is symmetrical. Small parts are more difficult to grip than larger parts (Larsson, 1986). Compact, non-slippery and parts with constant shape are easy to grip (Boothroyd, 1992; Holbrook *et al*, 1989; Norlin, 1970).

Round parts should ideally be designed with the centre line to be gripped coaxial to the gripper or the centre line of the robot (Andreasen and Ahm 1986). The centre of gravity for the part should be as close to the gripping position as possible (Larsson, 1986). Use surfaces for gripping that ensure that the part always is positioned the same way (Hallgren *et al*, 1992).

Screws with a long cylindrical body (length > 1,5 diameter) or long cylindrical head are easier to align compared to screws with a short body or head, since it facilitates the fitting process (Pettersson, 1977).

Equally large parts to be assembled should ideally be designed in one sequence, in order to lower the number of gripper changes, which saves time and money (Pontén *et al*, 1986). Changing a gripper does not add any value to the product.

Evaluation support:

Gripping is simplified if there are defined surfaces with determined geometry for use. Soft parts, e.g. plastics and rubber, are difficult to grip with a mechanical gripper since the parts can deform from the forces in the gripper.		**Man. ref. time**
Part has surfaces for gripping and can be gripped with the same gripper as the previous part.	9 points	0 s
Part has surfaces for gripping, but requires a new, unique gripper that could not be used for the previous part. Part has surfaces for gripping and can use the same gripper as used earlier, but not for the previous part.	3 points	0 s
Part has no surfaces for gripping or is flexible.	1 point	1 s

A.2.11 Assembly motions

All parts should be possible to assemble with one hand (Larsson, 1986). Manual assembly with one hand resembles automatic assembly.

One should strive for simple assembly motions when choosing fastening method (Engerstam, 1973; Legrain Forsberg, 1988; Pettersson, 1977). In Fig 66 different assembly motions are compared regarding their relative assembly speed. Fastening elements, or parts that are assembled using a combination of these motions, should be avoided. Pushing a part in place is preferable.

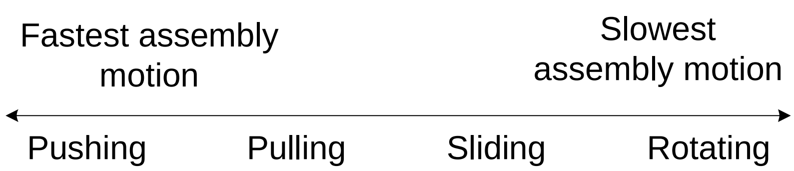


Fig 66: Comparison between the speed of different motions (Legrain Forsberg, 1988).

Evaluation support:

Assembly motions (during insertion) will be faster, the simpler they are.		**Man. ref. time**
Assembly motion consists of a pressing motion with one part being assembled to already assembled parts.	9 points	0 s
Assembly motion consists of further motions than pressing motion with one part.	3 points	0,5 s
Assembly motion is an operation with multiple movable parts that simultaneously are assembled to already assembled parts with other motions than pressing motion.	1 point	0,8 s

A.2.12 Reachability

There must be space for grippers and assembly tools around the part to reach for insertion and any special operations (Larsson, 1986; Pontén *et al*, 1986). Degrees of freedom in movements and assembly area should also be considered (Andreasen and Ahm 1986). Obstacles for insertion are to be avoided since they only cause complex movements or tools, which take time and can be difficult to programme.

Obstacles for special equipment, such as screwdrivers, must be avoided. It is also preferable that multiple screwdrivers can work in parallel to shorten the assembly time (Romnäs, 1972). Furthermore, it is vital to ensure that the space for further assembly is not limited (Boothroyd, 1992) see Fig 67.

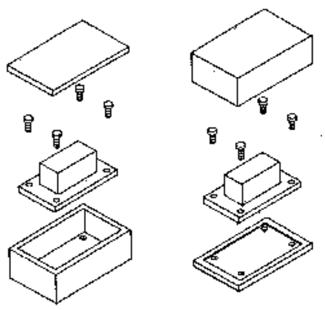


Fig 67: Simplify reachability for following operations.

Evaluation support:

Reachability for assembly operation should not be limited. All parts should be inserted in the same direction.		**Man. ref. time**
No restrictions or problems for reaching when fitting the part.	9 points	0 s
Reachability is limited. Other assembly direction than previous part.	3 points	4,5 s
Reachability is limited and requires special tools or grippers to perform the assembly operation. Other assembly direction than previous part.	1 point	7 s

A.2.13 Insertion

No parts, fixtures or anything else must act as an obstacle to the insertion of a part during the assembly process. The consequences of an obstacle are that the assembly system will be forced to perform more complex movements, which prolongs the assembly time and the programming time. The sandwich assembly principle (all parts are assembled on top of the previous) is desirable if there is a base object to start assembling from. Simple assembly motions and no obstacles while inserting parts can reduce assembly time.

The insertion of several parts at the same time should be avoided. If several parts have to be inserted simultaneously, they should have guiding surfaces to facilitate the assembly process (Andreasen *et al*, 1983; Boothroyd, 1992; Pontén *et al*, 1986). Parts that are symmetrical around their insertion axes are preferable, since this eliminates the need of a unique orientation for insertion (Boothroyd, 1992).

A peg-in-hole insertion operation is no problem for a human assembly worker, since we can use our senses. An automatic assembly unit has to be programmed to have these abilities, which takes time. The easiest way is to simplify the product to have a less complex insertion process. This can be done by the use of chamfers for parts that are to be inserted (Andreasen and Ahm 1986; Holbrook *et al*, 1989; Norlin, 1970), or by using guiding surfaces (Andreasen *et al*, 1983; Boothroyd, 1992), see Fig 68. It is sometimes wise to leave a small gap to compensate for tolerances that are not ideally derived (Holbrook *et al*, 1989; Pontén *et al*, 1986). Friction should be minimised between assembled parts, since high friction might require more sophisticated and expensive assembly equipment (Boothroyd, 1992; Larsson, 1986).

The following design aspects for screws can increase the availability for an automatic assembly system:

- Chamfered holes can prevent the first threads from being smashed.
- Holes with cylindrical openings are easier to fit into if the cylindrical section of the screw is fitted before the threads start working (Pettersson, 1977).
- Avoid assembling short screws in tight holes (Pettersson, 1977).

The design of a screw is especially important if the screw is short. A longer screw is simpler to align by the assembly equipment (Arnström *et al*, 1982). Screws with conical (half-dog point) or rounded ends, as well as pins (full-dog point), are easier to fit into (Norlin, 1970). A conical or chamfered end on a screw makes it easier to fit in and reduces the risk for damaging the threads (Pettersson, 1977). A pin reduces the risk for fitting the screw oblique, but can cause problems at the bottom of holes (Arnström *et al*, 1982). A Philips driver can help align a screw (Pettersson, 1977).

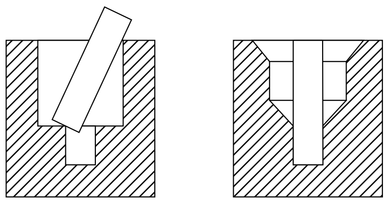


Fig 68: Chamfers may simplify insertion.

Evaluation support:

Insertion is simplified if there are chamfers or other guiding surfaces, e.g. an edge that can be used as a mechanical guide for the fitting operation, in the part.		**Man. ref. time**
Chamfers exist to simplify the insertion operation.	9 points	0 s
No chamfers, but other guiding surfaces simplifies the insertion operation.	3 points	0,2 s
No chamfers or other guiding surfaces.	1 point	0,5 s

A.2.14 Tolerances

High tolerances for parts should, where possible, be avoided since they entail higher manufacturing costs (Andreasen and Ahm 1986). For e.g. a fitting operation, the tolerance decides what equipment is needed.

Evaluation support:

Tolerances for insertion operations, for example the distance between a peg and a hole during insertion or whenever there is manipulation of parts relative to each other. Too small tolerances increases the risk of failure during insertion and the system could stop.		**Man. ref. time**
Tolerance > 0,5 mm	9 points	0 s
0,1 mm ≤ Tolerance ≤ 0,5 mm	3 points	0,2 s
Tolerance < 0,1 mm	1 point	0,4 s

See Fig 69 for a graphical representation of the evaluation criterion.

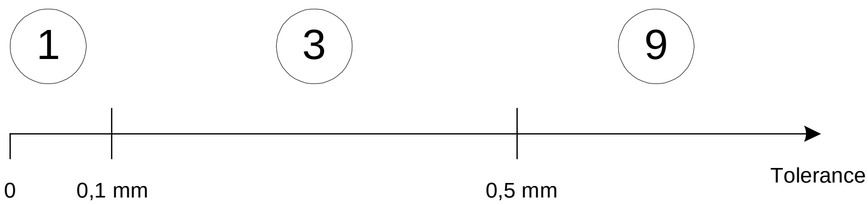


Fig 69: Graphical representation of the evaluation criterion "tolerance”.

A.2.15 Holding assembled parts

When the part is assembled in its place it should maintain its position without any external assistance (Boothroyd, 1992; Engerstam, 1973; Larsson, 1986), see Fig 70. This is especially important since extra equipment for holding parts requires space, increases costs and reduces the reliability of the system. The need for holding down parts may be minimised by using e.g. snap fits, secure placing of the centre of gravity, support, etc.

Using temporary support or holders in assembly can be very expensive. Therefore, design parts to be stable during assembly and can stand up without support (Holbrook *et al*, 1989). Parts should only have one stable state of rest

(Eversheim *et al*, 1982). If parts are not stable, the following operations will be less reliable.

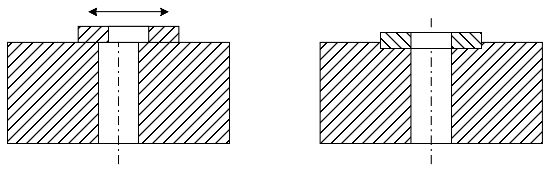


Fig 70: Parts should be able to keep orientation and position after being assembled.

Evaluation support:

Holding assembled parts is necessary if parts cannot keep orientation and position after assembly. Parts that are secured immediately, i.e. does not lose orientation or position if the assembly is turned up side down, ensures a more reliable assembly process.		**Man. ref. time**
Part is secured immediately at insertion.	9 points	0,s
Part keeps orientation and position, but is not secured.	3 points	0 s
Part must be held after insertion to keep orientation and position.	1 point	4 s

A.2.16 Fastening method

The numbers of fastening elements in a product usually determine the assembly time and should thereby be minimised. Number of fasteners can be minimised by integration of fastening elements in other parts (e.g. snap fits). It can also be accomplished by means of standardisation of fasteners. A product could contain fewer types of screw dimensions, screw types or different types of fasteners (Andreasen and Ahm 1986; Boothroyd, 1992; Engerstam, 1973; Holbrook *et al*, 1989; Larsson, 1986; Legrain Forsberg, 1988; Norlin, 1970; Pettersson, 1977; Pontén *et al*, 1986).

Assembling fasteners should entail few and simple motions to facilitate automatic assembly (Pettersson, 1977). If an extra fastener is needed, its assembly direction and assembly process should be identical to other fasteners (Andreasen and Ahm 1986). Snap fits can be designed for disassembly and service see Fig 71.

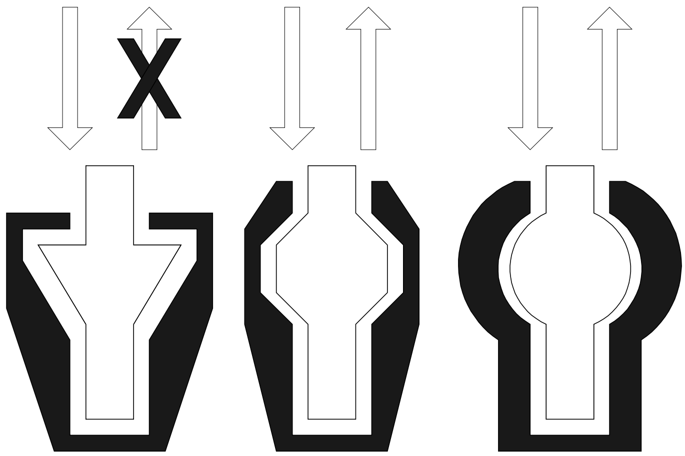


Fig 71: Examples of designing snap fits. The examples in the middle and to the right are suitable for disassembly and service.

The most preferable solution should be evaluated from the cost for developing a special tool, manufacturing integrated parts or eliminating parts (Ulrich *et al*, 1993).

Evaluation support:

Fastening method. How is the analysed part itself fastened?		**Man. ref. time**
No fastening method at all (the part is placed on or in an already assembled part), or only snap fits.	9 points	0 s
Screwing- or pressing operations.	3 points	3 s
Adhesive fastening methods, welding, soldering, riveting	1 point	8 s

A.2.17 Joining

Snap fits should be used where possible (Holbrook *et al*, 1989). The use of snap fits eliminates feeding of fastening elements and renders the joining of parts simple and fast. The benefits of using snap fits must be compared to potential problems in disassembly and orientating the part.

A part should be designed for easy and quick fitting, joining and securing (Larsson, 1986). This would simplify automation of the assembly process since many operations are simplified, the need for holding assembled parts is reduced and no separate tools such as screwdrivers are needed.

All joining, e.g. screwing, should be from the same direction, preferably from above. Gravity helps in the fitting and joining process of e.g. screws (Pettersson, 1977).

Evaluation support:

Joining: Extra equipment or tools (e.g. press tools or screwdrivers) should not be needed to fit the part into place.		**Man. ref. time**
No extra equipment is needed.	9 points	0 s
Extra equipment or tools are needed to fit the part in place and the extra operation is performed in assembly direction.	3 points	2 s
Extra equipment or tools are needed to fit the part in place and the extra operation is not performed in assembly direction.	1 point	3 s

A.2.18 Check/adjust

The product should be designed to have surfaces and points of reference from which the assembly starts (Norlin, 1970). Points of reference should be used throughout the whole production and also be points for positioning during fabrication.

Existing holes, edges, surfaces or shapes can be chosen for reference points (Pontén *et al*, 1986). Avoid placing reference points in parts that are likely to be changed. If there is a huge risk for redesign, in which the reference points will be moved, the whole process might be affected. Points of reference should be placed as far apart as possible (Larsson, 1986). Since points of reference are used for defining coordinate systems when programming the system they should be as far apart as possible to reduce sensitivity.

Points of reference and support for parts should, if possible, be in the same line (Larsson, 1986). Points of reference should be accessible as control points after assembly (Larsson, 1986). This can ensure easier and more reliable error detection and possibility to adjust.

A rule of thumb is to avoid any design that requires adjustments during assembly (Boothroyd, 1992). Adjustment operations are difficult and expensive to automate. In cases where adjustment cannot be avoided, design the product to have the adjustments performed as a separate operation after the automatic assembly. Parts should be designed to ensure clear controls with as simple sensors as possible (Pontén *et al*, 1986).

Designing parts that eliminate the risk of assembling the wrong way is called ”poka yoke” in Japanese (Holbrook *et al*, 1989; Larsson, 1986). It should be impossible to assemble the product in a wrong way. If parts still are assembled the wrong way it should be very visible in a finished product and the product should be refused for packaging. By designing products that are impossible to assemble the wrong way the need for checking and adjustments will be minimised, if not eliminated.

Evaluation support:

Check/adjust is not needed if the product is designed according to ”poka yoke”, i.e. it is impossible to assemble the part in more than one way. Every extra operation for checking or adjusting is extra work and a symptom of a design that is not quite satisfactory.		**Man. ref. time**
Unnecessary to check if part is in place.	9 points	0 s
Necessary to check if part is in place or assembled correctly.	3 points	1 s
Necessary to adjust or re-orient part.	1 point	2 s

A.3 Data sheet for product level

	PRODUCT LEVEL							
	Reduce number of parts	Unique parts	Base object	Design base object	Assembly directions	Parallel operations	Chain of tolerances	**SUM**
Objekt/Produkt/Modul								

Assembly index, A, is calculated through: $\frac{\text{Total sum}}{\text{Maximum points}}$ A = $\frac{\quad}{63}$ = %

A.4 Data sheet for part level

Part level

List of all parts	Number of identical parts	Need to assemble part?	Level of defects	Orientation	Fragile parts	Hooking	Centre of gravity	Shape	Weight	Length	Gripping	Assembly motions	Reachability	Insertion	Tolerances	Holding assembled parts	Fastening method	Joining	Check/adjust	SUM
																			TOTAL SUM:	

Assembly index, A, is calculated through: $\frac{\text{Total sum}}{\text{Maximum points * number of parts}}$ A = $\frac{\quad}{162 *}$ = %

A.5 Data sheet for cost analysis

Part/module/product	

Supposed manufacturing volumes	
Number of parts in the product	
Materials cost	
Development costs	
Item cost	
Variant cost	
Cassation	
Guarantee costs	
Other	

Part level, within system borders (focusing on the part alone during analysis).	Description						
	Is the activity needed? (*)						
	Machine time [S]						
	Labour time [S]						
	Setup time [S]						
	Tools [SEK]						
	Manufacturing equipment[SEK]						
	Comment						
System level, outside system border (the observer is standing outside the system during analysis).	Capacity [units/time]						
	Flexibility [units]						
	Maintenance [SEK]						
	Floorspace [M^2]						
	Comment						

*** Is the activity needed?**

1. Does the activity add **customer value** to the final product?
2. Is the activity needed to fulfil an external **requirement** (authorities, rules and regulations etc)?
3. Is the activity absolutely necessary to **manufacture** the product?

If all three questions are answered with "no", then there is no need for the activity. If one or more questions are answered with "yes", then the activity is needed.