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Modular Product Verifications Based on Design for Assembly

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Abstract

The desire to conquer markets through advanced product design and trendy business strategies are still predominant approaches in industry today. In fact, product development has acquired an ever more central role in the strategic planning of companies, and it has extended its influence to R&D funding levels as well. It is not surprising that many national R&D project frameworks within the EU today are dominated by product development topics, leaving production engineering, robotics, and systems on the sidelines. The reasons may be many but, unfortunately, the link between product development and the production processes they cater for are seldom treated in depth. The issue dealt with in this article relates to *how* product development is applied in order to attain the required production quality levels a company may desire, as well as how one may counter assembly defects and deviations through quantifiable design approaches.

It is recognized that product verifications (tests, inspections, etc.) are necessary, but the application of these tactics often result in lead-time extensions and increased costs. Modular architectures improve this by simplifying the verification of the assembled product at module level. Furthermore, since Design for Assembly (DFA) has shown the possibility to identify defective assemblies, it may be possible to detect potential assembly defects already in the product and module design phase. The intention of this paper is to discuss and describe the link between verifications of modular architectures, defects and design for assembly. The paper is based on literature and case studies; tables and diagrams are included with the intention of increasing understanding of the relation between poor designs, defects and product verifications.

1 INTRODUCTION TO PRODUCT VERIFICATIONS

Product verifications (from here on verifications) are the activities which a company performs, in order to obtain objective evidence of fulfilled product properties; and to deliver a defect free product to customers. Verification is an overall term and is synonymous with e.g. test, inspection or quality control. Objective evidence refers to quantifiable properties. Depending on the degree of embodiment of the product, the verifications aim to detect defects which originate from different areas within, and outside, a company, see Figure 1. The defects are deviations from, or lack of, the properties the product should embody to fulfill its quality. Verifications are therefore not targeting an increase in quality, but rather, detect any deviations from it. Here quality is used in broad terms since numerous definitions and descriptions exist. For example, [Garvin, 1987] suggests eight dimensions of quality (performance, feature, reliability, conformance, durability, serviceability, aesthetics and perceived quality). Or, the “fitness for use” discussed in the literature of J. M. Juran, e.g. [Juran *et al.*, 1974]. In the book “Quality is Free” Philip Crosby uses “conformance to requirements” to define quality, see [Crosby, 1980]. Crosby also implies that quality is not easily described or clarified with just one phrase, "Quality is ballet, not hockey". One may even interpret a product's quality as a fulfillment of properties. The better the properties meet the needs and demands, the more the quality increases; e.g. more "fitness for use" or more "conformance to requirements".

In general, verifications are a non-value added activity; thus, the customer may not be more satisfied by the product as a result of comprehensive verifications. Nonetheless, the customer may have specified certain types of verifications which could then be turned into a value added activity. For example, in the train industry the proof load should be well documented and conform to standards such as the Railway Group Standard [RGS, 2000]. However, the customer is interested in using the product and that the product works as expected, or even that it exceeds their expectation; they are not interested in how this has been accomplished.

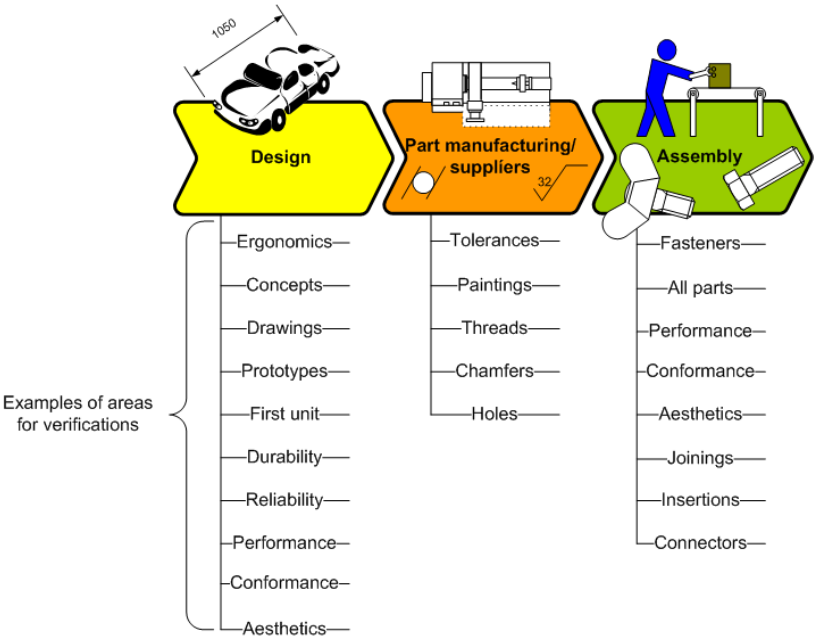

Figure 1: Examples of different areas of verifications depending on the degree of embodiment of the product, e.g. design, manufacturing and assembly.

Verifications would not be necessary if the defect rate was, commonly, zero. The concept of zero defects, originating from the US missile industry in early 1960s [Halpin, 1966], is still today in industry out of reach. In fact, the very meaning of the concept – a constant, conscious desire to do a job right the first time - is used as the quality motto in many companies. However, perfection in industries has not been attained, and will probably never be reached, due to the nature of human error, see also [Reason, 1990] and [Meister, 1989]. The experience assimilated is that there are no companies which are endowed with a defect free design, manufacturing or assembly; see also [Shingo, 1986], [Garvin, 1987], [Baudin, 2002] or [Katz *et al.*, 2002]. In fact, the success of Six Sigma tools [Bertels, 2003] which measure how near, or how far, companies are to 6σ quality may be proof enough of defective products or processes.

1.1 The cost of verifications and poor quality

Even though the cost to repair defects detected at a later stage (than where they occurred) may be difficult to estimate, rules of thumb can be used. [Robinson et al., 1990] mention the rule of ten;

i.e. it is ten times more costly to repair a defect late in the assembly line (or off-line) than it is to repair the defect when it occurs. One interviewed design manager used the rule of three which means that it is approximately three times more costly to correct a defective drawing compared to adjusting the defect where it occurred, for example at the concept development stage. If the defective concept is detected at part level, it is nine times more costly, and so on. Further, the later the defect occurs in the embodiment process the more time and resources it takes to prevent further defects, i.e. the feedback efficiency decreases. The feedback efficiency is the identification of the origin of the defect, and, for example, corrections to drawings and designs, correcting manufacturing processes and assembly instructions or methods.

As a fundamental basis, given that verifications do not add any customer value, one may argue that verifications are wasteful and should be eliminated as far as possible, or even completely; furthermore, the verification itself does not contribute to lowering the defects. On the other hand, eliminating verifications may increase the risks of having defect products shipped to customers, and so may not be an option.

Justification for verification is that it should decrease the cost of poor quality (COPQ). [Juran *et al.*, 1974] and [Juran, 1992] describes the COPQ as “costs which would disappear if no defects existed” or as “the costs which would disappear if our products and processes were perfect”. This description was further developed by [Sörqvist, 1998] who define internal and external cost of poor quality as follows:

> *Internal failure costs are losses caused by deviations from the desired quality level discovered before delivery to an external customer. External failure costs are losses caused by deviations from the desired quality level after delivery to an external customer.*

A decrease in the COPQ is achieved by defined verifications where any defects are detected at a desired point, close to the defect origin. Overall, the predictable cost of verifications should be balanced against the (less) predictable cost of repairing late detected defects (unwanted point of detection), including defects detected by customers [Nevins, 1989].

1.2 The aims of the work

The aim of the work described in this article is to discuss and describe the link between verifications of modular architectures, defects and design for assembly. Specifically how one may use results from DFA in order to perform concurrent work to decrease the lead-time in verifications at modular level. In section 2, a discussion on modular architectures is presented and the principle of verifying at modular level is described. Section 3 shows the link between poor design and the use of DFA. A practical case is outlined in section 4 which illustrates the benefits from DFA in relation to verifications at modular level. Section 5 provides a short summary of the paper.

2 VERIFICATION OF MODULAR ARCHITECTURES

The product architecture denotes the scheme of functional elements of a product, [Huang, 1999], and how these elements are arranged into physical blocks (modules) and the blocks’ interaction. [Huang, 1999] describes a modular architecture as the architecture where the functional element is implemented by one block, which has few but well defined interactions with other blocks. The integrated architecture is characterized by optimization of a certain performance. The interactions between blocks in an integrated architecture are not as defined as in the modular case, as each block embodies several functions. In the literature and in industry there are numerous advantages originating from modularization. For example:

- *Parallel activities in design, manufacturing and assembly*
- *Reduced part inventory (reduced storage, fixtures for manufacturing and assembly, purchasing activities, closer to supplier, economy of scale)*
- *Simplified generation of product variants*
- *Increased flexibility (faster response to changes such as new product- and re-design)*
- *Decreased product range complexity (fewer unique parts, manufacturing operations, assembly operations)*
- *The modular architecture with specified interfaces and properties create the possibility to perform verifications already at modular level.*

Previous work by [Erixon, 1998] has shown that the quality in the assembly system may be improved when modules are designed to admit separate functional testing. That is, only perfect modules are delivered to the main flow. The quality increase, which is achieved, is thereby due to the shorter feedback time of defect reports within the assembly module workshop. In Figure 2, the curves represent the number of parts building up a product. Specifically there is much to gain in the decrease of COPQ by performing module verifications on products with many parts (more than 500 parts).

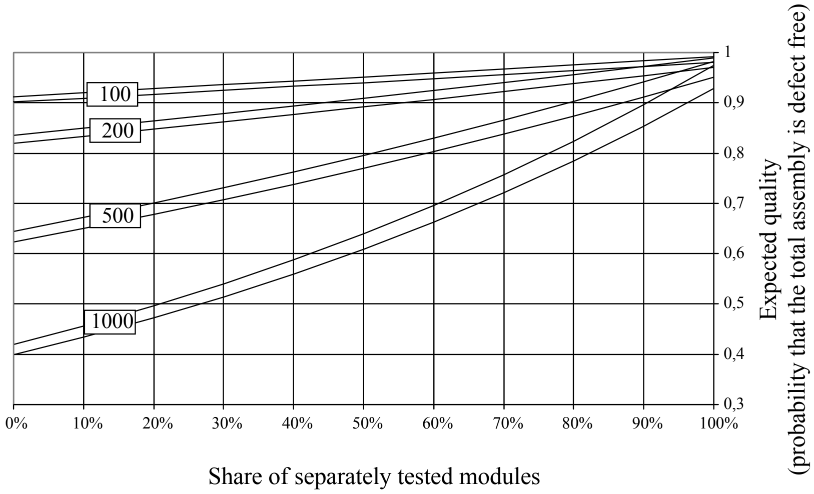

Figure 2: Probability for a defect free final assembly as a function of the percent of tested (verified) modules [Erixon, 1998].

Since a module has, or should have, specified interfaces and properties, it is possible to perform product verifications at module level. This verification at module level is called module property verification, MPV, see also [Kenger & Onori, 2003] and [Kenger *et al.*, 2004]. The verification of properties at product level is, here, called product property verification, PPV. The concept of MPV is to decompose the needs and demands at product level and verify them at module level instead of product level. This means that customer and internal needs and demands from standards and authorities are decomposed and described at module level. Furthermore, the results from the MPVs at module level give the resulting product property so that one can accept or reject the final product, see Figure 3.

There may be several benefits to gain from MPV instead of PPV, for example:

- *The verifications are decomposed to module level which facilitate planning and the performance of the verifications*
- *Decrease number of verifications on product level (decreases lead-time to customer)*
- *Increased probability of detecting defects (easier to detect 1 defect among 10 possibilities than among 100)*
- *Simplified repair of defects (fewer parts need to be disassembled and reassembled)*
- *Simplified share of modules between product variants (due to known and verified module properties)*
- *Bulky or heavy products (simplified handling)*
- *Orders may be available directly to final assembly (support the Assembly Initiated Production (AIP) concept) with verified modules in storage*
- *Reduced occupied space for spare parts and defective products*
- *Reduced amount of repair tools*
- *Easier to evaluate the verification (evaluation of fewer functions and with specified interfaces and properties)*
- *Flexible to abnormalities and defects (detection at module level gives faster response and feedback to the defect origin)*
- *Generic increase of "quality" (standardized tasks, verifications, and fewer functions and parts decrease the possibilities of making mistakes, and increase the awareness of what might go wrong)*

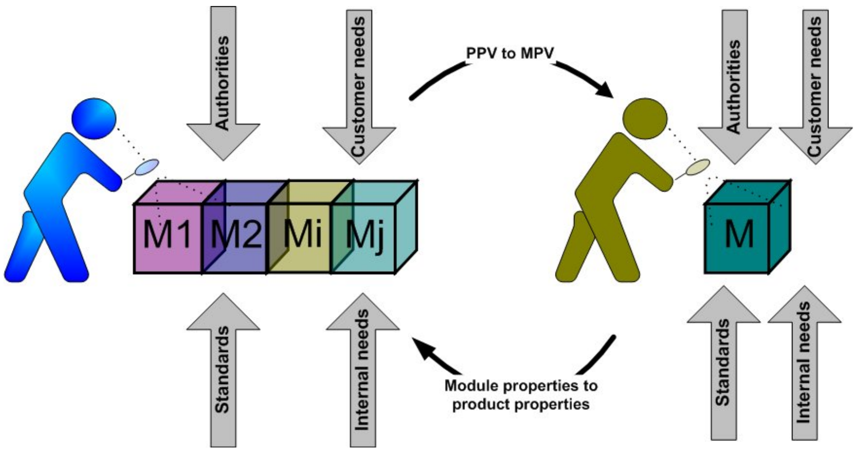

Figure 3: Schematically, a product which is built up by j modules and verified at product level (PPV), on the left, and on module level (MPV), on the right. The vertical arrows denote the needs and demands on the product which have to be decomposed from product level to module level. The verified properties at module level need to be translated back into product properties.

To avoid extended lead-times and increased costs due to PPV, companies can strive to move the product verifications to an earlier stage in the assembly. Preferably, the product verifications should take place at module assembly. If any defects are detected, the assembly personnel can adjust the defects directly as they are detected, using equipment and parts in the module assembly workshop. There is no need to transport the module to any PPV workshop, and there is no need for additional personnel in the module assembly workshop. Note, however, that performing PPV after assembly does not disturb the balancing of production lines, which may occur with MPV if defects occur (hence the need for buffers).

2.1 Industrial examples

ABB develops and assembles automatic and semiautomatic assembly systems e.g. for heavy diesel engines, and gearboxes. A heavy diesel engine line may consist of more than 50 automatic stations. Depending on the size of the system, parts or the whole system is put together at the company for a FAT, Factory Acceptance Test, where the customer can observe the system and test it. After the FAT the system is disassembled and shipped to the customer's site. The system is built up again and a SAT, Site Acceptance Test is performed. It would be valuable to ABB to assemble the lines, or stations, separately anywhere in the world and be sure that each station fulfilled its properties and are compatible with the other stations in the system, before realizing the system. This is a matter of standard solutions and modules, but also utilizes a MPV approach on station level, predicting the whole line property.

At another company, the defects from the integrated and modular products showed that the average defect rate increased by 21.5% – from 0.65 to 0.79 – when a modular architecture was implemented. At the same time, the assembly defect rate decreased to 12.5% and is 0.005 compared to the previous 0.040. However, the design defect rates have increased by 92% from 0.100 to 0.192. One may speculate several reasons for this change in defects and more specifically the increase in defect rates. Pahl and Beitz [Pahl & Beitz, 1996], for example, say that greater design efforts are necessary for a modular architecture. This effort is due to the overall function made possible by the combination of discrete units which need to be calibrated with each other. In addition, the greater the design effort the more design steps which may be defective. In fact, interviews with a project leader and design manager both said the same, that the modules are oversized. They have tried to "squeeze" in as many features as possible in each module in order to fit in more product variants and almost abuse the module driver "common unit" (see [Erixon, 1998]). One of the interviewees said that it is better to de-grade the module instead than up-grade.
The increase in design defects at the company may therefore depend on the following:

- *That the modular assortment is new to the company*
- *A greater design effort than previous is required*
- *Modules are oversized and packed with features*

What was clear from the study done at the company is that it is necessary to increase the verification activities, specifically at module level, in order to detect the defects as early as possible. However, what was not clear was what to verify; one does not want to perform any redundant verifications. At the same time, if the verifications are performed through MPV, all defects need to be detected at this point. Since, any defects detected at final assembly need to be sent back to the point of MPV that extends the lead-time; and because an assembly line design for MPV is not capable of detecting or repairing any defects at the final assembly, at least not to the same extent as an assembly line designed for PPV.

3 VERIFICATIONS AT MODULE LEVEL AND DESIGN FOR ASSEMBLY

Design for Assembly techniques and methodologies have been in use since the early 1980s. Not only has it become a known methodology, it has led to the spawning of many other approaches. Fourteen years ago, in the winter volume of DFMA Insight, [Branan, 1991] showed a relationship between defects per million parts and manual assembly efficiency, Figure 4. Since Motorola's defects increased when the DFA index decreased, Branan concluded that in order to increase assembly quality assembly needs to be simplified.

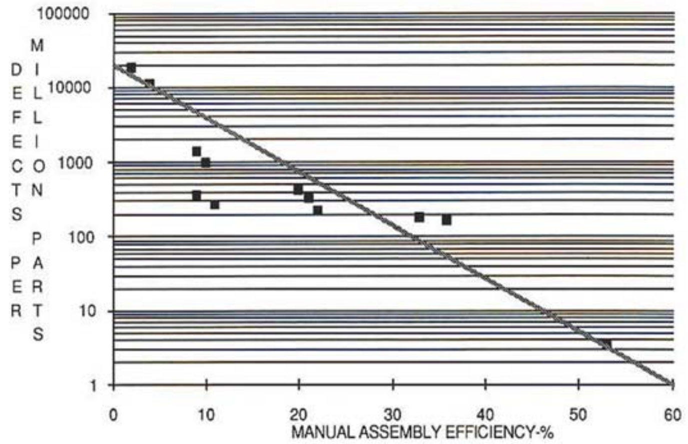

Figure 4: The relation between manual assembly efficiency and defect per million parts at Motorola [Branan, 1991]

[Barkan & Hinckley, 1994] analyzed this relation further and showed that longer assembly times are related to difficult assembly tasks which increase the probability that a defect may occur. They identified five assembly factors related to a qualitative product - (1) assembly operations, (2) assembly quality control, (3) assembly operation complexity, (4) number of parts, and (5) part defect rate. Today the DFMA software from Boothroyd Dewhurst Inc. estimates the defect probability based on the assembly difficulty and the company's Six-Sigma level. This in turn gives the design team an excellent opportunity for proactive actions, instead of reactive work such as late calls for redesign, rework at the shop floor, reassembly, or customer complaints. The author's own studies, Table 1 and [Kenger, 2004], have shown similar results; long assembly times may be related to an increase in defects.

Table 1: The relation between assembly time and defect rate

Assembly time	Defect rate		Assembly time	Defect rate
< 0.5 hour	< 0.01		0,5 to 1 hour	0.2 to 0.5
<0.5 hour	< 0.01		1 to 2 hours	0.2 to 0.5
< 0.5 hour	< 0.01		2 to 3 days	0.2 to 0.5
0,5 to 1 hour	< 0.01		2 to 3 days	0.2 to 0.5
1 to 2 hours	< 0.01		>2 weeks	0.2 to 0.5
1 to 2 hours	< 0.01		1 to 2 hours	0.6 to 1
5 to 10 hours	< 0.01		1 to 2 hours	0.6 to 1
< 0.5 hour	0.01 to 0.1		> 2 weeks	0.6 to 1
< 0.5 hour	0.01 to 0.1		2 to 3 hours	1.5 to 2
<0.5 hour	0.01 to 0.1		5 to 10 hours	2.1 to 5
0,5 to 1 hour	0.01 to 0.1		2 to 3 days	5.1 to 10
1 to 2 hours	0.01 to 0.1		1 to 2 weeks	5.1 to 10
2 to 3 hours	0.01 to 0.1		> 2 weeks	5.1 to 10
3 to 5 days	0.01 to 0.1		> 2 weeks	5.1 to 10
3 to 5 hours	0.01 to 0.1			

A case study performed at a company, covering 1600 defects reported over an 8 year period, was analyzed (further discussion in [Kenger, 2004]). The design and assembly defects were plotted against each other in order to analyze a possible correlation, Figure 5. The sample correlation coefficient was shown to be 0,83 which is a strong relation, [Johnson, 2000]. This in turn implies that a difficult design later on also causes the assembly operators to make mistakes.

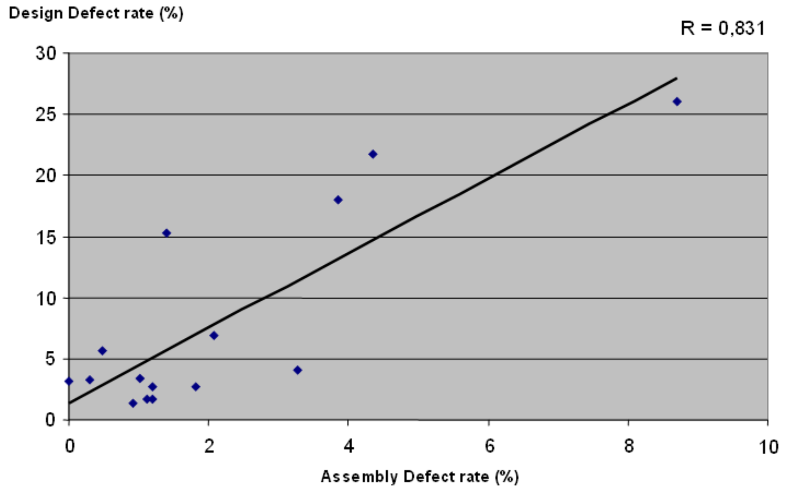

Figure 5: The correlation between design and assembly defects in one studied company. Each dot represents the result from one delivered order. The design and assembly defect rate in percent is related to the total (100%) of all occurred defects in each order.

Since the general trend is an increasing number of product variants, the companies' product assortment also becomes more and more complex. Complexity is difficult to define or describe, and is sometimes only a gut feeling or a subjective interpretation. For example, as told by one of the engineers at one studied company, "a complex product involves many steps that can cause a defect". The steps the engineer referred to were design, manufacturing and assembly. This was also confirmed in one of the products at the studied company in which, among others, the pneumatic system contains many parts and functions. The product was considered (perceived by the personnel) to be more complex than usual and had 212 reported defects in the project which produced the pneumatic system; the average number of defects was 96 in 15 studied projects.

[Magee & de Weck, 2004] quantify complexity and define a complex system as "a system with numerous components and interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change". A system is "a set of interacting components having well defined behavior or purpose". According to [Magee & de Weck, 2004] complexity may also be related to the amount of information needed to describe the system; or related to the number of unique elements in the system and their interconnections. Complexity according to [Pahl & Beitz, 1996] is the "lack of transparency between inputs and outputs". They also mention that a relatively large number of assemblies and components, and intricacy in manufacturing processes, is considered complex. [Hubka & Eder, 1988] suggest a classification of technical systems according to their complexity. A low degree of complexity in the parts or subassemblies is said to be more suitable for use in different applications compared to a high degree of complexity such as in production systems. One may say that it is the parts which create this complexity in companies, as most of the activities a company performs relates to the number of product variants, manufacturing and assembling of these variants. In the end, this means that parts need to be designed, manufactured and assembled (purchased, stored, supplied and sold).

By reducing the complexity the verification process is simplified, since fewer parts need to be verified and less interactions between parts in different modules need to be considered. All in all, the overall quality of a product will increase if the complexity decreases. Here, both modularization and design for assembly (DFA) help to decrease the complexity; modularization by using the same or similar modules in several product variants, and DFA by eliminating or combining the parts in the product.

4 DFA TO IDENTIFY POTENTIAL DEFECTS IN MODULES – A PRACTICAL CASE

Since it is possible to get a first insight into a product's defect potential from the DFA analysis, this can be used to increase the feedback efficiency and the concurrent engineering. The feedback efficiency is increased since parts or subassemblies with a relatively low DFA index give an early opportunity to redesign areas that may have a potential for defects. The concurrent engineering is increased due to the possibility to start planning and preparing for the verification already at the design phase of the product or module. This in turn makes it possible to begin the design of test fixtures and verification instructions for assemblers and test personnel. This planning is time consuming and take several weeks to carry out.

A European company, which produces products for the train industry, has been studied for several years. Their products are strictly ruled by demands from laws, standards and customers; thus, no defects are acceptable and the products always need to work properly year after year. However, fulfillment of the demands is cost and time consuming and extends the lead-time to delivery. This lead-time extension is among others caused by the necessary work at the tests department where the following pre-production verification (prior to the product being put into production) is performed:

1. A test document is written and sent to the customer, specifying how the test will be carried out and what will be tested.
2. The customer accepts or rejects the test document (if not, the procedure starts again at 1).
3. On acceptance, a more extensive test document is written which specifies the following:
    a. Pre assembly, and test and measurement of all parts
    b. Design of new fixtures
4. The type test is performed (taking approximately 3 days and involving two people). If any defects are detected it takes 2-3 days to redesign if the parts are made in-house, approximately 2 weeks if the parts are purchased externally.
5. Internal FAI (First Article Inspection), which is a complete inspection and functional test of a fully assembled and painted product. The internal FAI takes 3 hours and involves one person from the quality department, 1 test engineer, 1 project designer, 1 from after sales, the project leader, 1 assembler, 1 production engineer, and 1 purchaser. If any defects are detected the whole group meets again, once the defect is repaired, for a new internal FAI.
6. External (customer) FAI, similar to the internal FAI but where the customer is present. The external FAI takes 1-2 days and involves the project leader, 1 project designer, 1 person from the quality department, 1 test engineer and the customer.

It takes 1-2 weeks for the test engineer to finish the tests and write the test documents. However, it takes 1-15 days for the test engineer to design a new test fixture, depending on size and function. It takes approximately 8 weeks until the test fixture is manufactured and ready for use.

The fixture itself costs on average $1500. In Table 2 an approximation is made of the tasks, lead-time and cost of performing the tests and approving the product.

Table 2: Average time and costs to perform pre-production tests (given a defect free design)

Test task	Lead-time (days)	Man-hours	Costs ($)[1]
Write test documents	5	40	3360
Design fixture	8	64	5376
Receive fixture	40	-	1500[2]
Perform type test	3	24	2016
Perform internal FAI	0,4	24	2016
Perform external FAI	1,5	48	4032
Summary	*57,9*	*200*	*18300*

The company uses a modular architecture; however, the assembler verifications (verifications performed during production) are performed through PPV, i.e. at the completely assembled product level. The company's aim is to increase verification as much as possible at module level through MPV. For this reason, it is important to identify new verification tasks for module level. Today, the majority of the assembler PPV is performed with computerized gauges, manual inspections, and different types of measurements. The module assemblers, on the other hand, perform manual self-inspections of their own work and mark essential screws and fasteners with color and fragile paste to show that a verification is performed, Figure 6. However, in MPV, more of the product's properties need to be verified already at modular level.

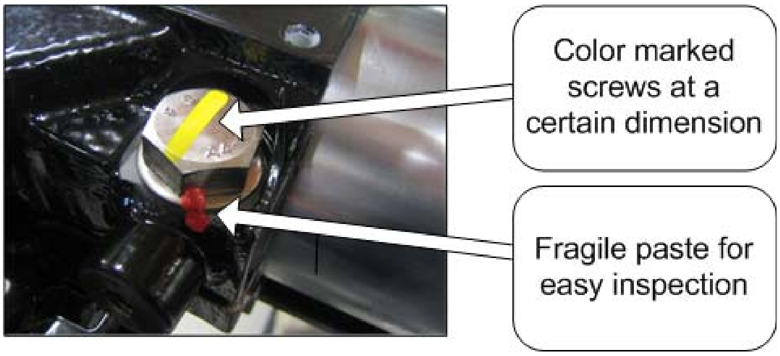

Figure 6: Verifications at module level

One of their modules was relatively expensive to manufacture and assemble, thus a DFA analysis was performed using the methodology described in [Boothroyd & Dewhurst, 1989], [Boothroyd *et al.*, 2002] and the DFMA software from Boothroyd Dewhurst Inc., Figure 7. Specifically one component of the module had a DFA index of 6.45.

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[1] Based on a cost of 600 Swedish crowns per hour which corresponds to approximately $84, 30th of May 2005

[2] This is the cost to purchase the fixture

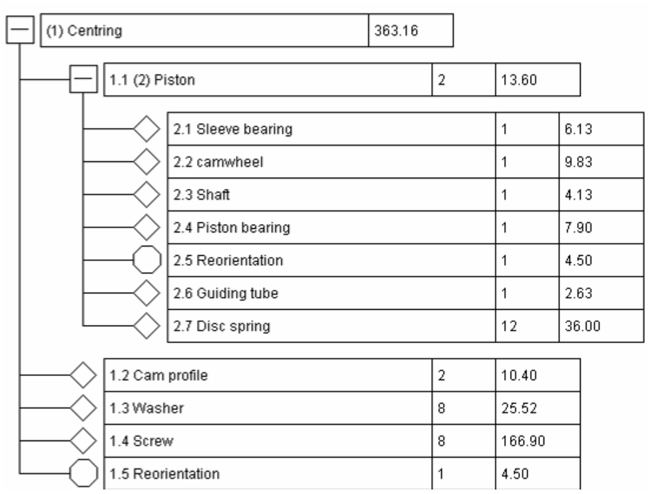

Figure 7: Assembly sequence of a module component.

One of the reasons for the low DFA index is the disc spring, Figure 8. There are 24 discs which need to be assembled in pairs towards each other. The pistons and the discs are then inserted into a cylinder from two opposing directions. The insertions of the piston and the 12 pairs of discs are difficult to overview during the assembly operation, and are perceived by the assemblers as difficult.

Figure 8: Left: the piston and the guiding tube which the disc spring are inserted onto. Centre: the disc spring needs to be in 12 pairs of discs on the pistons. Right: Finally, the pistons with the springs are inserted into the cylinder from two opposing directions.

The component with the piston and the disc spring is essential for the module's property and any defective assemblies are, of course, not acceptable. The low DFA index, on the other hand, indicates a potential for the component to be defective. For example, according to the results from Motorola in [Branan, 1991] shown in Figure 4, a DFA index of 6.45 may result in 6000 ppm.

It is clear that in order to prevent a defective module being supplied to the final assembly, additional assembler verifications should be performed. Also, concurrent with the first DFA, the test documents and activities, made at the pre-production and assembler verifications, can be supplied with valuable information. For example, potential defective parts or components in a module and test fixtures which need to be made. This concurrent work decreases the lead-time in pre-production and assembler verifications illustrated in Figure 9.

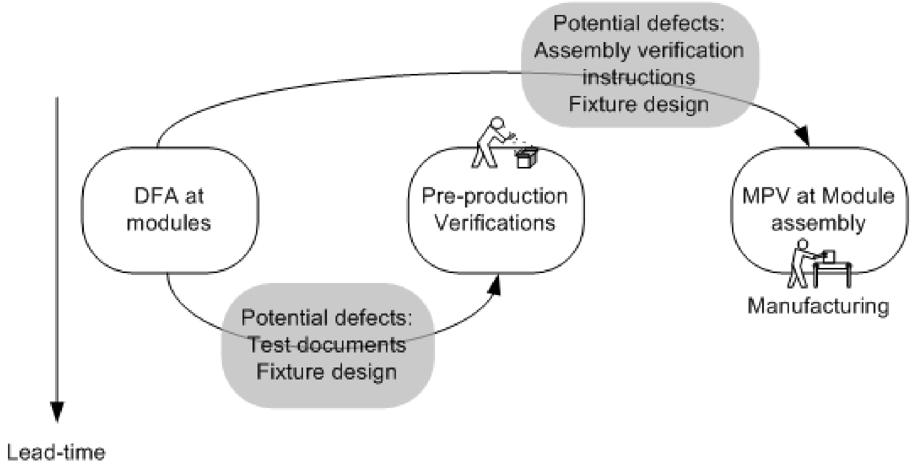

Figure 9: Schematic illustration of how results from DFA analysis are forwarded to pre-production and module verifications. The results are potential defects in the designs which give information to prepare test documents, fixtures and instructions for MPV.

5 SUMMARY

The experience gathered has shown that there is a need to focus design work on defect reduction. Proactively this is done with the zero defect concept, thus "do it right the first time" and to "build in quality" in the products. Paradoxically, however, this leads to companies applying great efforts to fight defective work which not only results in them losing customers but extends the lead-time and increases costs. Clearly, it is necessary to identify more efficient ways to be reactive and to verify products before shipment. The paper has shown that modular architectures offer the opportunity to verify at module level, called module property verification, MPV; which has several benefits, such as increasing feedback efficiency and facilitating repair of defects.

In this context, DFA can be used to identify potential defects at the early stages of product design. The paper shows studies where long assembly times, low DFA-indices and poor designs ultimately cause assembly defects. The link between DFA, modular architectures and product verifications has been used in the paper to illustrate how work can be performed concurrently. The idea is that results from DFA analysis are used to point out potential defects. When any potential defect is identified, information is forwarded to the personnel at pre-production- and assembly-verification. The work to prepare test documents, instructions and fixtures can then start already during the design of the product or module.

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