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STUDIES OF DESIGN AND ASSEMBLY DEFECTS ON INTEGRATED AND MODULAR ARCHITECTURES

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Abstract

It is known that despite companies' efforts to improve the quality of their products, design and assembly defects results in large repair costs both in terms of repair and providing feedback to the origin of the defect. The purpose of this paper is to study these types of defects and the defect rates in design and assembly. The paper presents a web based questionnaire answered by 29 companies. The result shows that the defect rate (defects per product) spanned from 0.01 to 10. Also, design and assembly defects covered 46%, 23% respectively, of all occurred defects. A case study is also presented, performed at a company who recently implemented a modular architecture. In this company, defects from 5 700 integrated product architectures are compared with defects from 431 modular architectures. The average defect rate increased by 21.5% – from 0.65 to 0.79 – when a more modular architecture has been implemented. Furthermore, the study showed that the assembly defects have decreased while the design defects increased. The results presented in this paper will also support the development of the MPV (Module Property Verification) method which is briefly described.

Keywords: Defect statistics, Product architectures, Modularity and Standardisation, Property verifications

1 Introduction

Product verifications (from here on verifications) are the activities a company performs to obtain objective evidence of fulfilled product properties; and to deliver a defect free product to customers. Objective evidence means that the properties should be measurable. The defects are deviations from, or lack of, the properties the product should embody to fulfil its quality. Verifications would not be necessary if the defect rate was always zero. Today, however, perfection in industries is not yet reached, and will probably never be reached due to the nature of human error, see Reason [19]. The operator errors which caused the nuclear disaster in Chernobyl [20], and the design errors underlying the Estonia tragedy [9] are sad examples of human error potential and poor design. Lawrence and Kosuke [15] also describe 13 cases of fatal designs which resulted in large lawsuit outlays.

The experience assimilated during this work is that no companies are endowed with a defect free design, manufacturing or assembly; see also Shingo [22] and Baudin [2]. In fact, the success of Six Sigma tools [3] which measure how near (or how far) companies are to 6σ quality may be evidence itself of defective products or processes. Hales [8] clearly underlined the problems with poor design at the 2003 ICED conference. He said that even "the simplest and most fundamental design methods, guidelines, rules and recommendations are still not understood, accepted or used by many who claim to be competent engineers". Similar conclusions can be drawn from other authors. For example, Carlsson [5] presents 15 studies of the use of DFMA (Design for Assembly and Manufacturing) within Swedish companies. The conclusion from [5] is that the methods are not utilized to their full potential, which in turn depends on three reasons: ignorance of the methods, wrong priorities, and work overload. In addition, Martins [16] surveyed 19 companies in the UK on the use of QFD (Quality Function Deployment). The result was that the most common problem with QFD implementation was time consumption, lack of knowledge and managerial support. In fact, out of the 19 companies, six have stopped using the method as a result of implementation problems. From this somewhat compelling introduction it is clear that methods and tools to deliver defect-free products still need to be dealt with by the design research community. In addition, improvements to methods and tools to verify the designs and assemblies need to be properly tackled.

2 Background and motivation for the work

Previous work [7] 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 should be 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 (team work area). Even though the cost to repair defects detected at a later stage may be difficult to estimate, rules of thumb can be used. Robinson [21] mentions 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 as 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 – at the concept development stage, see Figure 1. If the defective concept is detected at part level it will be nine times more costly, and so on. Further, the later the defect occurs in the 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 defect origin, and, for example, corrections to drawings and designs, correct manufacturing processes and assembly instructions or methods. Basically, in Figure 1, the feedback efficiency is the proactive activity - time and resources - needed to prevent the same defects from occurring again; and the defect repair is the reactive activity to repair one defect.

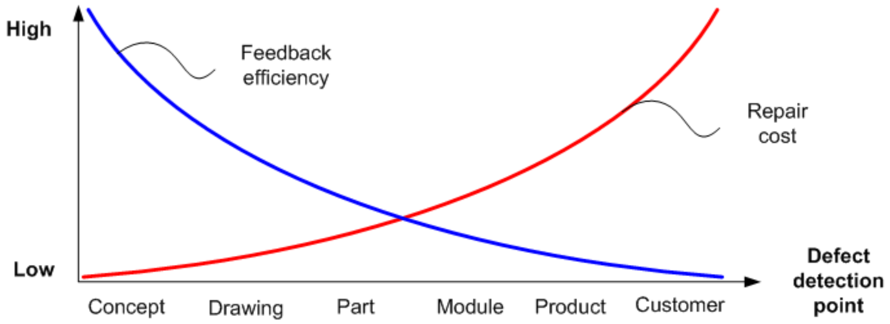

Figure 1: Schematically description of repair cost and feedback efficiency depending on the defect detection point. Here, the defect origin is the concept development and corrections needed to be made to the concept.

Ideally, all defects should be detected at the moment they occur. However, some defects may be impossible to detect until they make themselves known. For example, a defective part may not be detected until the final assembly; or, the product's final performance will be rather difficult to verify from one single part. Although a modular architecture is beneficial when it comes to verification, repair of any defects, and to provide feedback on the origin of the defect. These benefits are due to the defined blocks (modules) which embrace one or more defined functions. Ulrich and Tung [24] said that “because components in a modular design correspond to particular functional elements, the function of the component is well defined and a functional test should be possible”.

2.1 Product verifications at module level

A methodology to perform verification on modules is under development, so-called MPV (Module Property Verification), see [14] or [13], with the aim to enhance the benefits from a modular architecture by:

- Decreasing the cost and lead-time in verifications
- Providing faster feedback in order to decrease the number of defects

However, the number of defects per product (defect rate) affects the verification strategy one chooses to use. In this paper we will distinguish between three verification strategies:

- Verifications which are performed at the module assembly workshop, i.e. MPV. Only defect free modules are supplied to the final assembly or to an intermediate storage to decrease the lead-time from order to delivery.
- Verifications which are performed through MPV at a joint station.
- Verifications which are performed at product level at the final assembly workshop, so-called PPV (Product Property Verification).

These strategies are illustrated in Figure 2 which schematically shows a product made up by *j* modules. The product properties are illustrated as black arrows where each module fulfils one property. The dashed arrow represents a product property which is shared among three modules. The four boxes, one on each product property arrow, represent the different verifications strategies.

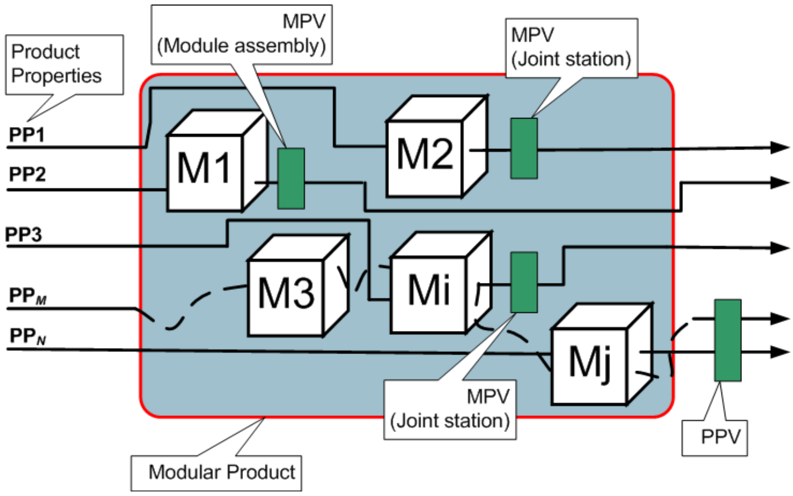

Figure 2: A modular product built up by *j* modules with its properties represented as arrows, and verifications represented as boxes on each arrow - schematic illustration.

Even though there are several benefits to be gained by performing MPVs, there may be reasons for performing the verifications at product level – the PPV strategy. PPV may be more beneficial to perform when the number of defects per product (defect rate) is relatively low. Only a final check of the product is performed as a precaution to ensure the compatibility of the parts or modules making up the product. Compared with MPV, there are fewer separate verifications in PPV since one PPV might correspond to several MPV's. That is, at module level each module may need its own verification while it may be sufficient with a single verification at product level.

The questions one may ask are therefore: what are the defects rates in companies, and are there any defects which occur more often than others? Furthermore, are there any differences in how defects occur in a modular architecture compared to an integrated architecture? The answers for these questions may enhance the understanding of how defects occur, which in turn may support a decision on the best verification strategy to use. We decided to use a questionnaire to survey companies' products and defects, and also to case study one company which is implementing a modular architecture. In this company we had the opportunity to compare defect statistics from an integrated architecture with those from a modular architecture.

3 Working methodology

Twenty-seven Swedish and two Norwegian companies answered a web based questionnaire. Initially, eighty-nine Swedish and ten Norwegian companies were contacted, initially by phone (to get in touch with personnel with the knowledge and responsibility for quality issues), and then by Email (to provide the link to the web page). The companies we contacted were assembling companies with more than ten employees. We have not surveyed any specific branches or products. The web based questionnaire proved to have both advantages and disadvantages. The advantage was that the respondent could relatively easily answer the questions compared to using paper and pencil and posting it back to the interviewer; the web based questionnaire has probably increased the answering frequency (approx. 30% of the Swedish and 20% of the Norwegian companies). This relatively low number of responses should according to Ejvegård [6] not be subject to any analysis. However, the questionnaire regarded how companies dealt with defects, which is something that companies prefer not to discuss in detail (due to the negative purport of defects). And, it is believed that the answers from the 29 companies give an insight into the subject of defects. The answers were transferred to an Excel sheet and could easily be analysed, compared to answers on paper. The web based questionnaire had the following questions and is discussed in chapter 4.

1. What is the major assembly method used?
2. Does the product contain modules or subassemblies?
3. How many parts does the product contain?
4. Does the company (or department) keep a record of defect statistics?
5. Are there strategies or methods to reduce the number of defects?
6. Estimate the number of defects that may occur per product.
7. If a defect should occur, what is the most common cause of this defect?
8. Estimate in hours the time it takes to assemble the product.

4 Defects in 29 companies

The first three questions dealt with the product and how it is assembled. Table 1 shows that 23 companies or 88.5% mainly use manual assembly for their products. Regarding the question if the product is made up by modules or subassemblies most of the companies, 23 out of 28, have a modular architecture or a product which is made up of subassemblies. The number of parts per product is shown in Table 3 where most of the companies have either up to 100 parts or more than 501 parts.

Table 1: Assembly method at 26 companies

Assembly method	*Answers*	*Percent distribution*
Manual	23	88,5
Automatic	3	11,5

Table 2: Product architecture at 28 companies

Modules or subassemblies	*Answers*	*Percent distribution*
Yes	23	82,1
No	5	17,9

Table 3: Number of parts per product at 29 companies

How many parts does the product contain?	*Answers*	*Percent distribution*
1 to 25	6	20,1
26 to 100	5	17,2
101 to 250	2	6,9
251 to 500	2	6,9
501 to 1000	6	20,7
1001 to 3000	4	13,8
>3001	4	13,8

In Table 4, 27 companies out of 28 claim to have a record of defects; and all of the 28 responding companies in Table 5 say they have a method or a strategy to reduce the number of defects.

Table 4: Defect record in 28 companies

Record of defects	*Answers*	*Percent distribution*
Yes	27	96,4
No	1	3,6

Table 5: Methods or strategies to reduce defects in 28 companies

Methods or strategies to reduce defects	*Answers*	*Percent distribution*
Yes	28	100
No	0	0

Table 6 shows the answer to the question how many defects per product the companies have. As can be seen, 15 companies or 51.8% claim they have less than one defect per ten products. Also, 4 companies or 13.8% have between 5.1 and 10 defects per product. Table 7 shows the estimated defect distribution in percent in 19 companies. The difference between material and manufacturing is that material is purchased parts and raw material, and manufacturing refers to in-house manufactured parts. Table 7 is summarized in Figure 3 where the average percent defect distribution per cause is shown. In Figure 3 it is seen that design and assembly defects each cause 23% of the defects and that material causes 21%. The most common cause for a defect is in-house manufactured parts which represent 33% of the defects.

Table 6: Estimated number of defects per product from 29 companies; rounded up to one decimal point

Number of defects per product	*Answers*	*Percent distribution*
< 0.01	7	24,1
0.01 to 0.1	8	27,6
0.2 to 0.5	5	17,2
0.6 to 1	3	10,3
1.1 to 2	1	3,4
2,1 to 5	1	3,4
5,1 to 10	4	13,8

Table 7: Defect distribution in percent, estimations from 19 answered companies.

Company	*Assembly %*	*Design %*	*Material %*	*Manufacturing %*
Company 1	30	30	10	30
Company 2	30	30	10	30
Company 3	20	30	-	50
Company 4	25	25	50	-
Company 5	25	25	35	15
Company 6	10	-	20	70
Company 7	25	25	-	50
Company 8	20	20	30	30
Company 9	60	20	20	-
Company 10	40	20	20	20
Company 11	25	-	25	50
Company 12	25	25	-	50
Company 13	30	50	-	20
Company 14	40	20	-	40
Company 15	20	20	40	20
Company 16	-	55	30	15
Company 17	20	10	20	50
Company 18	10	20	-	70
Company 19	25	25	20	30

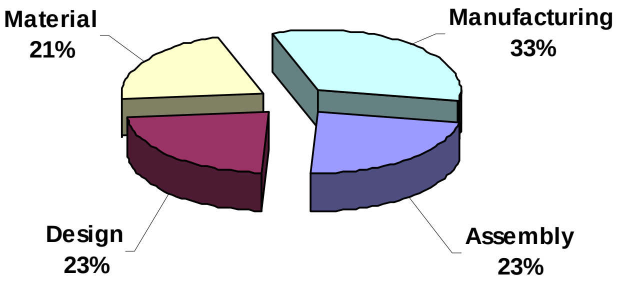

Figure 3: Average defect distribution in 19 companies, based on Table 7.

Branan [4] showed a relationship between defects per million parts and manual assembly efficiency. This relation was further analyzed by Barkan and Hinckley [1] who showed that longer assembly times are related to difficult assembly tasks which increase the probability that a defect may occur. In Table 8 the assembly time from 29 companies is shown in relation to their defect rate. Table 8 shows similar results as [1], for example assembly time from <0,5 hours to 15 hours has a defect rate of <0,01; assembly time from <0,5 hours to 4 days has a defect rate of 0,01 to 0,1; assembly time from 0,5 hour to >2 weeks has a defect rate of 0,2 to 0,5; and assembly time from 2days to >2 weeks has a defect rate of 5,1 to 10.

Table 8: Assembly time and defect rate in 29 companies

Assembly time	*Defect rate*
< 0.5 hour	< 0.01
<0.5 hour	< 0.01
< 0.5 hour	< 0.01
0,5 to 1 hour	< 0.01
1 to 2 hours	< 0.01
1 to 2 hours	< 0.01
6 to 15 hours	< 0.01
< 0.5 hour	0.01 to 0.1
< 0.5 hour	0.01 to 0.1
<0.5 hour	0.01 to 0.1
0,5 to 1 hour	0.01 to 0.1
1 to 2 hours	0.01 to 0.1
2 to 3 hours	0.01 to 0.1
2 to 4 days	0.01 to 0.1
3 to 5 hours	0.01 to 0.1
0,5 to 1 hour	0.2 to 0.5
1 to 2 hours	0.2 to 0.5
2 to 4 days	0.2 to 0.5
2 to 4 days	0.2 to 0.5
>2 weeks	0.2 to 0.5
1 to 2 hours	0.6 to 1
1 to 2 hours	0.6 to 1
> 2 weeks	0.6 to 1
2 to 3 hours	1.5 to 2
6 to 15 hours	2.1 to 5
2 to 4 days	5.1 to 10
1 to 2 weeks	5.1 to 10
> 2 weeks	5.1 to 10
> 2 weeks	5.1 to 10

5 Defects in Integrated and Modular Architectures

The product architecture denotes the scheme of the functional elements of the product, Huang [10], and how these elements are arranged into physical blocks (modules) and the blocks' interaction. Furthermore, Huang [10] and Ulrich [23] describe a modular architecture as the architecture where the functional element is implemented by one block which has few but well defined decoupled interfaces between other blocks. The integrated architecture is typically 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. Figure 4 illustrates a scale in which the left shows a 100% modular architecture with defined block and interfaces; and the right shows a grey area as the integrated architecture where there is no clear distinction between blocks or functions. Every product fits in somewhere on this scale depending on the degree of modularity.

Since modularisation reduces the number of parts in a product, see [7], there are reasons to believe the defect rate will decrease as well [1]. To study any change in defects a case study was performed at a company who recently changed from modular to integrated architecture.

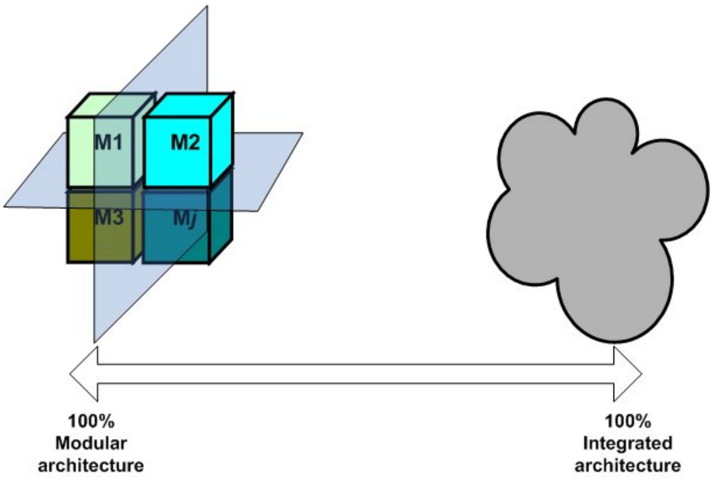

Figure 4: Modular and integrated architecture illustrated as defined blocks and a grey area.

5.1 A case study at Company δ

Company δ is a subcontracting company which develops and manufactures products made up of 2000-3000 parts. They deliver approximately 2000 products per year. It takes normally up to two years, or even more, to deliver all the products for one order. Company δ has been working with a modular architecture for approximately 3 years and estimate in a near future a decrease in number of different parts in the total assortment; and at the same time an increase in product variants with the same working effort as today, see Table 9. Company δ strives to have a modular architecture for 80% of the products; 20% will remain to allow customization. However, they estimate that this 20% customization will demand 80% of the total effort.

Table 9: Changes in Company δ from 30 years of integrated architecture to three year of modular architecture

Product architecture	*Years*	*Variants*	*Number of different parts*
Integrated	30	300	10 000
Modular	3	7 000	3 000

The case study at Company δ was performed as proposed by Yin [25] who says that “the case study method allows investigators to retain the holistic and meaningful characteristics of real life events – such as individual life cycles, organizational and managerial processes… and the maturation of industries”. Irrespective of the application, there are 5 fundamental components in a case study [25]: (1) a question to be answered, (2) an initial proposition, (3) a unit of analysis, (4) the logic linking the data to the propositions, and (5) the criteria for interpreting the findings.

In Company δ, a detailed study of 6 131 delivered products and design and assembly defects was performed; 5 700 products having an integrated architectures from 17 delivered projects and 431 products from five project with a modular architecture, see Table 10. The modular projects S, U and V in Table 10 are still awaiting delivery. Referring to Yin [25], the objective with the study was identify the defect rate in the integrated and modular architectures, and to detect any differences in how the defects occur. We used their defect database to obtain the defect descriptions, the unit of analysis being the defect rates.

Table 10: Defect statistics from Company δ and 17 projects with an integrated architecture and five with a modular architecture.

Integrated architecture	*Delivered products*	*Defect rate*	*Assy. defect rate*	*Design defect rate*
Project: A	45	1,44	0,044	0,222
B	210	0,42	0,005	0,057
C	52	1,98	0,212	0,365
D	1088	0,14	0,012	0,017
E	63	0,81	0,000	0,032
F	78	0,99	0,038	0,179
G	1083	0,20	0,012	0,028
H	330	0,44	0,003	0,033
I	72	1,18	0,014	0,153
J	69	0,96	0,087	0,261
K	295	0,41	0,010	0,034
L	122	0,45	0,033	0,041
M	144	0,41	0,021	0,069
N	238	0,64	0,092	0,101
O	986	0,11	0,009	0,013
P	715	0,16	0,011	0,017
Q	110	0,38	0,018	0,027
	Tot. 5700	Av. 0,65	Av. 0,040	Av. 0,10
Modular architecture				
Project: R	102	0,70	0,010	0,167
(awaiting delivery) S	12	1,25	0,000	0,417
T	125	0,56	0,000	0,088
(awaiting delivery) U	32	0,88	0,000	0,156
(awaiting delivery) V	160	0,56	0,013	0,131
	Tot. 431	Av. 0,790	Av. 0,005	Av. 0,192

5.2 Defects in the integrated architecture

The defect rate in the 5, 700 integrated products in Table 10 varied from 0.11 defects per product to 1.98. The defect rate includes production-, supplier-, reclamation-, storage-, welding-, painting-, logistic-, design and assembly defects. However, only the design and assembly defects are discussed in this paper. Furthermore, the average defect rate from assembly is rather low, 0.04, compared to the design defects which are 0.10. Further, as shown in Figure 3, there may be grounds to believe that design and assembly defects can be of the same rate. However, in Company δ, the assembly defects where normally detected and reported by the assemblers themselves. According to one of the assemblers, at least 50% of the assembly defects were never reported to the defect data base. Instead, the defects were corrected by the assemblers and afterwards nobody knew that the defect had ever occurred. Thus, any improvements to prevent future assembly defects will be difficult to make. And, even if assembly defects are reported to the defect database; self inspection by the assemblers is not always efficient since it is difficult to find faults in their own work [2].

We were also interested to see if the design defect rate changed during the time of the delivery of the order. The total time for delivery was divided into three equal thirds. For each third we counted the number of design defects as a percentage of all defects. The result in Figure 5 shows that only 2 out of 17 projects have more design defects in the last third compared to the first third. That is, as the delivery of the orders progressed the defect rate decreased.

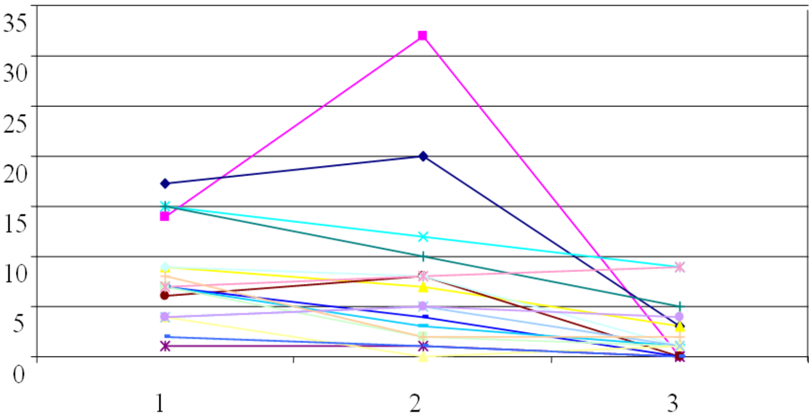

Figure 5: Design defects in 17 integrated product projects. The Y-bar shows, per project, design defects in percent in relation to the total number of defects. The X-bar shows the 1st, 2nd and 3rd part, in time, of each project's delivery.

All design defects from the 17 projects were tested for goodness of fit to a normal distribution. Two of the 17 projects were identified as outliers and were removed before the normal distribution test. However, the p-value (the risk of faulty reject the null hypothesis of normal distribution) was 0,086, indicating that the design defect rate is probably not normally distributed.

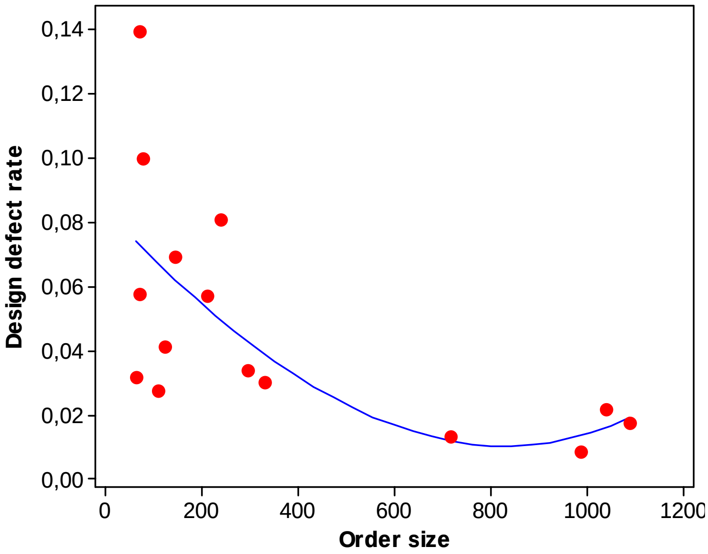

Figure 6: Design defect rate as a function of the order size in 17 projects with an integrated architecture. The sample correlation coefficient (R-sq) is 0.42 for a cubic regression.

Finally, the design defects from the integrated architecture were mapped against the order size. Figure 8 shows the design defect rate as a function of the order size in the 17 projects. The sample correlation coefficient (R-sq) is 0.42 for the third degree polynomial regression, shown in Figure 8, which is a weak correlation according to [12]. A strong correlation is near 1 or -1. The sample correlation coefficient was even weaker for second and first degree polynomial. Therefore, it is not possible to predict any future defect rate, based on the curve equation, if the order size is known. However, it is possible to see a pattern where the design defects decrease as the order size increases.

5.3 Defects in the modular architecture

The modular architecture in Table 10 has an average defect rate of 0.79, assembly defect rate of 0.005 and design defect rate of 0.192. Similarly, as with the integrated architecture, the total times for delivery were divided into three equal parts. For each third we counted the number of modular design defects as a percentage of all defects. In Figure 7, two-fifths (2/5) of the projects have an increase in design defects in the final third of the delivery process. However, in 3 of these 5 modular projects the orders are awaiting delivery and the defect rate may decrease in the last third (similar to the integrated architecture, see Figure 5).

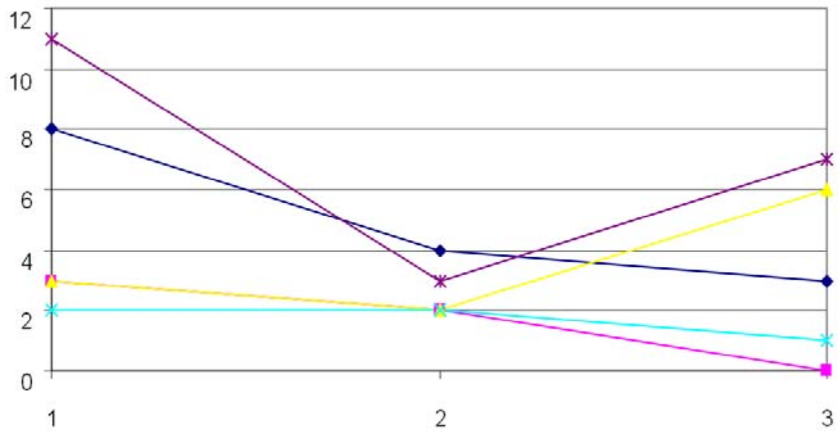

Figure 7: Design defects in five modular projects. The Y-bar shows design defects per project and percent in relation to the total number of defects. The X-bar shows the 1st, 2nd and 3rd part, in time, of each project's delivery.

As with the integrated architecture, the design defects from the 5 projects were tested for goodness of fit to a normal distribution. Again, the p-value was low (0.039) indicating that the design defect rate is probably not normally distributed. Figure 8 shows the design defect rate as a function of the order size (delivery so far). A curve linear regression was made for the 1st, 2nd and 3rd degree polynomial but no good correlation was reached.

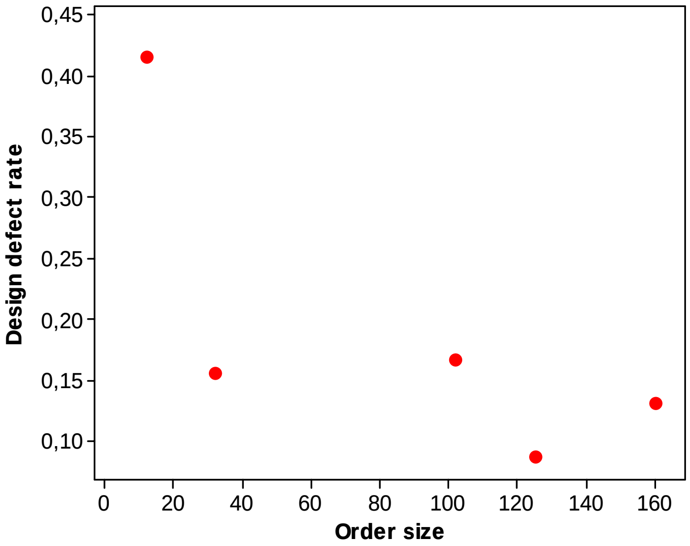

Figure 8: Design defects as a function of the order size in 5 projects

5.4 Summary and discussion

The questionnaire showed that the majority of the companies claim to have a modular architecture or a product made up of subassemblies. The questionnaire also showed that design and assembly defects may represent almost half (46%) of average occurred defects. MPV is not applicable at part level (given that a part is not a module) only at module level during design and assembly. Since 46% of the defects originate from design and assembly there is an obvious need to improve companies' methods and tools to prevent and detect these kinds of defects. MPV is one way to reach this improvement.

The defects from the integrated and modular products at Company δ showed for example that the average defect rate increased by 21.5% – from 0.65 to 0.79 when a more modular architecture has been implemented. At the same time the assembly defect rate has 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 [17] 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. One has 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" described in [7]. One of the interviewees said that it is better to de-grade the module instead than up-grade. The increase in design defects may therefore depend on the following:

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

To work with verifications at modular level (MPV) during the design process would help the company to decrease the defect rates and provide faster feedback regarding the origin of a defect. Since MPV has not been possible on previous integrated designs, it is believed that the modular design defect rates will decrease below the integrated design defects in the near future.

The decrease of modular assembly defects to a level of 12.5% compared to the integrated architecture assembly defects may depend on several issues. First, it is known that 50% or more of the assembly defects are never reported. However, the same routines and the same workshops with the same personnel may indicate that other things play a part as well. Since the modular architecture is more defined and built up of fewer parts, this may affect the defect rate as well. However, one of the designers has regular contact with the assembler and said that the assembler's experience is that the modular architecture is more difficult to assemble. The reason for this was that the assemblers have built-in routines for the integrated architecture and the introduction of the modular architecture has changed these routines. Thus, the new modular assembly requires a new and "unfamiliar" way when assembling the product. However, one of the modular projects which has been delivered, project T in Table 10, did not report any assembly defects, which has never happened before.

Economies of mass- production and customization have been discussed by Jiao and Tseng [11], see Figure 9. The discussions in [11] may be applicable to the defect rates as well. Mass production is beneficial for high volumes where the sales volumes cover the cost of investments in equipment, tooling and training. However, at low volumes, mass production cannot cover the cost of investments with the return from sales. Mass customisation, on the other hand, allow companies to gain scale of economy through repetition which reduces costs and time [11]. Here, a modular architecture is considered by Pine [18] to be the best strategy for mass customisation.

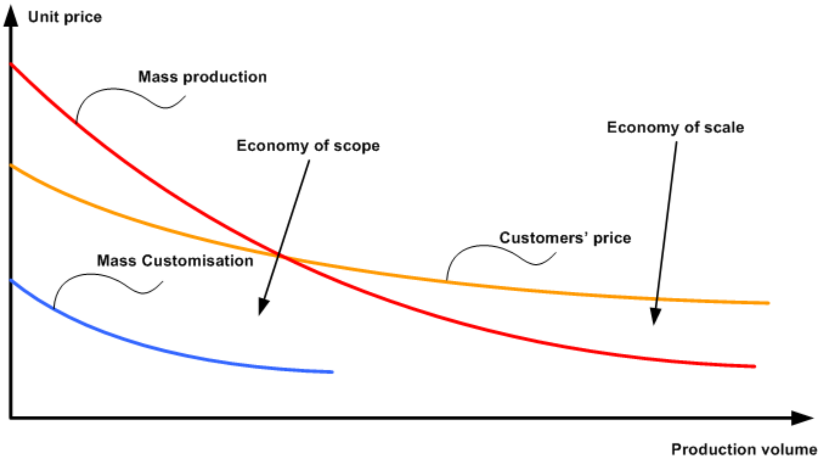

Figure 9: Due to economy of scope, mass customisation is profitable even at low volumes. Mass production demands larger volumes to be profitable in order to cover the cost of investments, example from [11].

In Figure 6 the pattern of design defects for the integrated architecture showed that the defect rate decreased as the order size increased. That is, the cost to repair and provide feedback decreases in projects with relatively large order sizes compared to the costs for smaller orders. In Figure 9 this repair and feedback cost can be compared to the economy of scale for the unit price for mass production. However, there are no indications so far that the modular design defect rates in Figure 8 will give decreased repair and feedback costs for small order sizes – economy of scope. The two modular projects which have been delivered in their entirety had design defect rates at 0.70 for 102 products and 0.56 for 125 products. These numbers are larger than similar order sizes from the integrated architecture in Figure 6. Possible explanations for the lack of economy of scope, i.e. the relative high integrated design defect rates, were given above.

6 Conclusions

The defects studied in this paper have enhanced the understanding of how defects occur and the defect rates present in design and assembly. That defects occur is known to the design research community as well as among companies. Numerous major accidents are living proof of the result of defective designs or assemblies; as well as each company's costs to repair defects and to provide feedback on the origin of the defect.

Twenty-nine (29) companies have been surveyed via a web based questionnaire which showed that defects are present in all answered companies, and that the defect rates (defects per product) spanned from less than 0.01 to between 5 and 10. The survey also showed that all companies work with methods or tools to reduce defect rates. The average defect distribution was 23% for design and assembly, 21% for purchased material, and 33% for in-house manufacturing. A case study with the aim to study the defect difference in integrated and modular architectures has been presented; the studied company had changed from an integrated architecture to a more modular architecture. The study showed that the average defect rate in the company increased by 21.5% in the modular architecture; the design defect rate increased by 92% and the assembly defect rate decreased down to 12.5% of the previous rate. As greater design efforts are necessary for a modular architecture, and as the company has oversized the modules, the increase in design defects compared to the integrated architecture may be explained by: (1) the modular assortment being new to the company, (2) a greater design effort being required, and (3) modules being oversized and packed with features in order to be a common unit.

The MPV method aims to improve companies' possibilities to detect defects and to perform verifications at module level, and thereby also decrease the feedback time. The aim of this paper was therefore also to provide input for further development of the method. Specifically, the studies have shown that defects are common in every company and that new methods and tools are needed to improve the efficiency in handling these defects. The case study showed that economy of scope from modular architecture has not yet been reached due to a relatively high number of design defects. However, economy of scope may be reached by verifications at modular level. Further research and more studies of this kind are necessary in order to have a clearer picture of defects in a modular architecture and how these should be tackled.

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