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AN APPROACH TO EVALUATE PRODUCT VERIFICATIONS

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Companies implement a module product assortment as a part of their strategy to, among others, shorten lead-times, increase the product quality and to create more product variants with fever parts. However, the increased number of variants becomes a challenging task for the personnel responsible for the product verifications. By implementing verifications at module level, so called MPV (Module Property Verification) several advantages ensue. The advantages is not only a decrease in cost of verifications, but also a decrease in repair times, occupied space, storages with spare parts, and repair tools. Further, MPV also give an increased product quality due to an increased understanding of which defects that may occur. As an approach to implement MPV, this paper discusses defects and verification processes based on a study at a Swedish company. It also describes a matrix which is used to map relations between company specific cost drivers and so called verification factors. The matrix may indicate cost drivers which have a large impact on the total cost of product verifications.

Keywords: Modularization, Verifications, Defects

1 Introduction and Objective

To keep up with increased volumes and product variants companies strive to implement a modularized product assortment. Modularization has shown to have numerous benefits, see e.g. Peng (2003), Ulrich and Tung (1991), Erixon (1998), Stake (2000), or Baldwin and Clark (2000). In fact many Swedish companies have successfully utilized modularity to stay competitive. Among these are Scania and VBG, see Erixon (1998), ABB, VOLVO, and ITT Flygt, see Stake and Blackenfelt (1998). One studied company shows a potential increase of 6700 variants (theoretically possible variants) and a decrease of 7000 parts after a two years implementation of modular products. However, the number of new variants made possible and introduced in the assembly line has its own properties, and need its own specific verification. In this paper, verification denotes the process of determining whether or not the product at a given phase in the life-cycle fulfils its properties. This definition includes the commonly used word test, but also manual inspection and quality control, and the planning, evaluation and documentation of the verification results. The personnel who perform the verifications face an impossible task due to modularity: verifying increasing volumes and variants with the same amount of personnel and equipment. This is the case at one company where the actual verification process has become the bottleneck. One way to handle lead-time and cost of verification is to reduce the verification itself. Although this will cut cost and time, Varma (1995) points out that it is more important to focus on product profitability and verification strategies. Also, to have less verifications may not be an option for companies, governed by standards and laws related to tests.

Even tough modularity creates a challenging task for the verification personnel, modules themselves has proven to have benefits related to defects and verifications, see e.g. Kenger, P., (2004), Kenger and Onori (2003), Erixon (1998), Nevins and Whitney (1989), and Baldwin and Clark (2000). By implementing a strategy to verify products on module level, so called MPV (Module Property Verification) has several advantages such as, shorter repair times, less occupied space, less stocks with spare parts, less repair tools, increased product quality, and an increased understanding of which defects may occur. Also, researchers have discussed advantages of decomposing complex products into multiple sub-functions, e.g. Pimmler and Eppinger (1994), Pahl and Beitz (1996) Hubka and Eder (1988), Svendsen and Hansen (1993). These sub-functions are generally easier to handle than the complete product, and the solutions to the functions can be derived in parallel. In addition, by decomposing heavy or bulky products into smaller components (modules) the handling of products during the verification is simplified.

The objective with this paper is to discuss product defects, how they may occur, as well as verification possibilities using MPV at module level or PPV (Product Property Verifications) at product level. The paper shows the use of a tool which maps the relations between drivers that affects the total cost of verifying products and so called verification factors. The discussions in the paper is based on own experiences from studying a Swedish company for a two year period, as well as interviews with more than 15 persons from the personnel. Also, the discussions on defects are based on the company's own defect reports.

2 Introducing Product Defects

Assembly is the process of putting together manufactured parts in order to complete a product. The DFA index in Boothroyd et al. (2002) has shown to be a measure of the products potential to be wrongly assembled. The DFA index have been used for this purpose by Motorola, described in Brannan (1991), and further developed by Barkan and Hinckley (1994). Own studies, described in Kenger (2004), have also indicate a relation between design defects and assembly defects which further underline the relation between DFA index and defects. Here, a defect is a fault that causes the product not to fulfill its properties, i.e. the product does not work or have the intended appearance. Defects themselves are a symptom of poor machines, designs and routines where the defect origin is claimed to always be human. External defects refers to supplier defects and are supplied parts from outside of the company and taken into the production process. Internal defects are made inside the company and refer to manufacturing-, assembly-, and verification defects. Verification defects mean that even though the product is subjected to a physical test, wrong properties may be tested. This in turn may result in a defect passing the test and on to customer. Verification defects may also be that the physical test ought to measures the right property, but either the operator and/or the test gauges interpret the results correct. Again, this may result in defects passing the test. After the final verification of the product, only defects which could not be detected are delivered further on to customers. These defects are related to expensive repairs and loss of goodwill. In Figure 1, the studied company's relation between defect types, point of detection, and repair cost is shown. Figure 1 show that the repair cost can be 1000 times higher if the company needs to e.g. send two personnel from Sweden to USA for a repair, compared to repairing the defect at part level were the defect occurred. In Figure 1 the following defect types is used. (I) *Part defects* - The part is defect due to machine operator mistake, machine tolerances or handling. (II) *Design defects* - The design is defect (does not work as intended) due to wrong way of thinking. (III) *Assembly defects* - The assembly is defects due to use of wrong parts, incorrect insertion or missing part. These assembly defects is also mentioned in Nevins and Whitney (1989) who also point out assembly defects caused by damaged part that is used anyway, dirt or other contamination between parts, and damaged caused by insertion or handling. Not shown in Figure 1 are the verification defects since this defect type may be involved in type I, II and III. The verification defect means that the verification itself is incorrect in that sense that the defects are not detected and the defective product is delivered to customer or next assembly station. As indicated above, the verification defects can be of two kinds:

- *Operator/Equipment* error – the verification is performed on the right part(s) or function(s) but the operator/equipment is not detecting the defect
- *Planning* error – the wrong part(s) or function(s) is verified making it possible for defects to pass without being detected.

The difference between operator/equipment and planning error is that operator/equipment error is made at the time the verification is performed, while the planning error is made earlier were the decisions is taken of which parts and functions that will be verified.

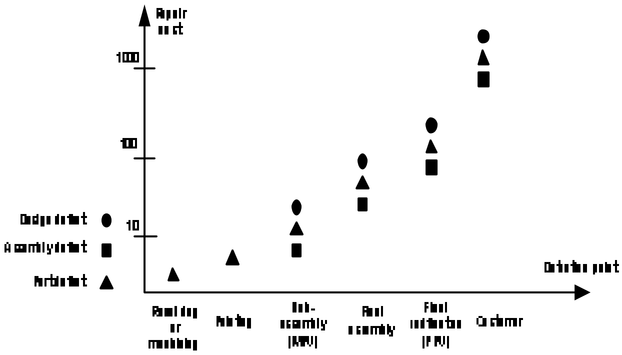

Figure 1: Schematically, the cost of repairing defects at a certain detection point.

The repair of defects in the studied company contained the following four measures. (I) *Part defect* – rework, scrap or part redesign, (II) *Design defects* – redesign, (III) *Assembly defect* – disassembly and reassemble the correct part(s), disassembly and reinsertion, making sure all parts available, and small sub-assemblies may be scrapped, (IV) *Verification defects* - adjust equipment and tools, adjust to verify right properties, and check operator routines. The range of sources for defects increases with every stage in the chain from design to final assembly and verification. The closer in time the product is to the customer, the probability of having defects increases. One way of decreasing the number of defects occurring from assembly would be by decrease the number of operations in the assembly process, decrease the number of assembled parts, or by decreasing the complexity of the assembly operations. Modularization is offering this opportunity and will be enhanced further by modules designed or adapted for verification. This is confirmed by statistics described in Erixon (1998) showing that the separate testing of modules decreased the amount of rework by 37-75%, with a median of 56%.

3 Concepts of Property Verifications

There are numerous reasons for considering the verifications, the benefits can be e.g.:

- Shorter lead-time
- Increased product quality
- Decreased repair cost (see further discussions in e.g. Juran and Gryna (1980) pp.12-15 on internal and external costs)
- Decreased test costs (by testing only what's necessary)

Further, since the verification should detect any defects, it offers the opportunity of seeing the weak points (the defects) of the product, which in turns makes it possible to optimize the product assortment. According to projects and defect reports at the studied company, defects caused costs for millions SEK per year. These costs have forced the company to make, among others, the verification process more cost effective and strive to implement MPVs.

In studied companies, as well as the one discussed in this paper, the major part of the verifications takes place at or after final assembly, i.e. PPV, and can be summarized as in Figure 2, where there are two options to repair defect products and to perform PPV. PPV needs storage for defect products, an additional storage for spare parts, and if chosen, an additional repair workshop. Time to customer is extended by the time the PPV takes. In PPV it is more difficult and expensive to repair any defects since the product is fully assembled.

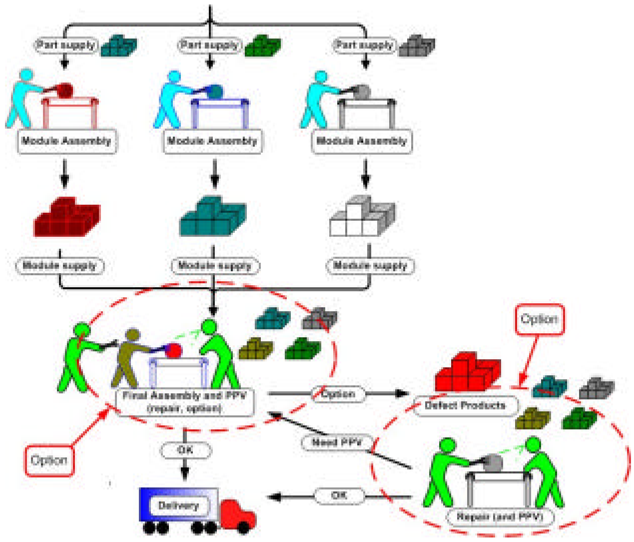

Figure 2: Product property verifications (PPV) at final assembly.

To avoid extended lead-times and increased costs due to PPV, companies can strive to move the product verifications to an earlier point in the assembly. Preferably the product verifications should take place at module assembly, Figure 3. If any defects are detected, the assembly worker 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 workers 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).

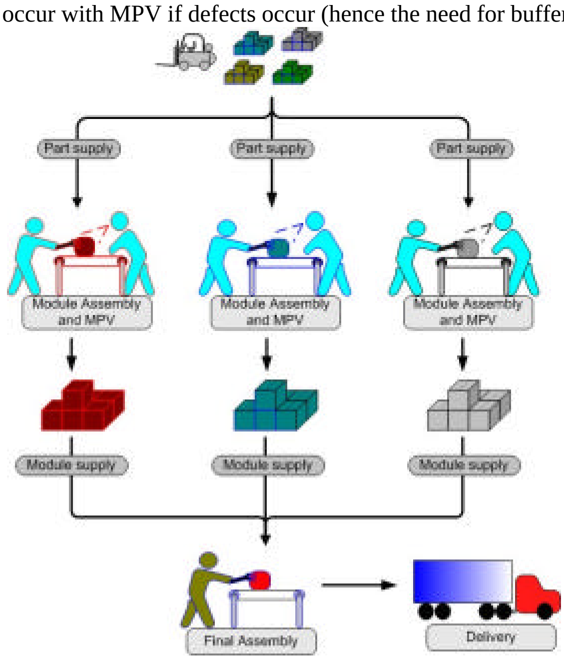

Figure 3: Module property verifications (MPV) at module assembly.

In order to have an efficient verification, the MPV should be integrated into the activities of the module assembly workshop, using quality control charts and flexible test and assembly fixtures enabling adaptation to changes necessary for module variants.

Even though there are several benefits by performing MPVs, there may be reasons for performing the verifications at product level, PPV. PPV may be more beneficial to perform when the number of defects per product (defect rate) is relative low. Only a final check of the product is performed as a precaution to ensure the compatibility of the parts or modules building up the product. Compared with MPV, there is less number of 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 enough with a single verification on product level. All in all, it is necessary to evaluate the benefits of MPV compared to PPV to avoid costly rearrangements at the point of verification which in turn affects both the assembly system and the module design.

The company discussed in this paper performs the major part of their verifications at product level, i.e. PPV. Therefore an analyze of the present PPV was made with the purpose to (1) allocate and identify costs of verifications, and (2) compare future concepts of MPV with present PPV to select the most time and cost effective verification.

4 An Approach to Evaluate Verifications

During product verification several steps are made (e.g. planning, documentation, testing, evaluating, and moving and storing products) and it is essential to identify value added work. Costanza (2003) points out that by identifying value added steps it is possible to increase the percentage of value-added work and eliminate the non value-added. The product verifications are often considered as a non-value added activity; see e.g. Costanza (1996) or Baudin (2002), since it does not add any value to the customer. If the verifications are treated as non value-added, or *muda* (waste) as in Womack and Jones (2003), it would be removed.

However, the verification process cannot be removed completely since zero defects still are an utopia for many companies, as well as verifications them selves are demanded by governments, or standards. Therefore, it is necessary to keep track of the costs and cost drivers related to verifications in order to eliminate non value-added work. By allocating the costs of verifications it provides opportunities to identify critical areas that need improvements. Cost accounting as the ABC-method, see e.g. Ax and Ask (1995), can been used to allocate both cost of defects as well as of verifications. However, in the beginning of identifying the cost of verification a coarse mapping will provide guidelines of what is driving the costs. Here the term cost driver is a variable that affects costs. That is, [any change in the cost driver will cause a change in the total cost of a related object], Horngren et al. (1994). In this paper the following verification factors, from here on factors, are used in which cost drivers are mapped against:

- *Cost to perform* (C_P) verifications is the cost related to time and economical resources needed to carry out the verification. The C_P is related to the number of needed verifications, complexity of the product, time to perform the verifications, and number of workers needed.
- *Cost to repair* (C_R) occurs when there are defects in the product. There are many cost drivers which influence C_R, for example how many parts need to be disassembled for the repair and how workers is needed.

In addition, it is necessary to take into account the following probabilities as factors that influence verifications since it will affect the total cost of having verified and defect free products delivered to customers.

- *Probability that defects occur* (P_O) denotes activities that will affect the probability that defects will occur.
- *Probability that defects are detected* (P_D) denotes the activities which affect the probability that an occurred defect is detected

In order to identify which cost drivers that affect the factors, the studied company's own defect reports were used, as well as interviews with production engineers. The relationship between factors and cost drivers for the company where mapped in a matrix, see Table 1, using 1, 3 and 5, where,

- 5 - Strong relationship
- 3 - Medium relationship
- 1 - Weak relationship

No mapping between factors and cost drivers means that no relation was identified during the time of the study. However, the way of numbering relations may always be questioned and interpreted as a subjective approach to indicate relationships. Yet in this case, a first mapping with the used relations was found suitable. In Table 1 the relations are summarized both column- and row wise at the bottom and to the right respectively.

Table 1: Mapping of factors and cost drivers

Cost Driver / Factors	Facility space	Workers	Product complexity	Repair equipment	Storage	Time	Verification equipment	Verification method	Impact
C_p	3	5	3		1	5	5	5	**27**
C_R	3	5	5	5	3	5			**26**
P_O		5	5			5			**15**
P_D		5	5			3	3	5	**21**
Impact	**6**	**20**	**18**	**5**	**4**	**18**	**8**	**10**	

The reason that "Time" is a separate cost driver and not included in the others is that some verifications consumes time while the workers can work in parallel with other tasks, but nevertheless extends the lead-time in verification. Based on Table 1 the following analyze and discussions can be made.

In order to perform verifications (C_P), "time", "workers" and "verification equipment", are needed which is why these cost drivers have the strongest relationship with C_P. There is a medium relation between C_P and "facility space" and "product complexity". Space does not have strong relation on C_P because the company has available space for the PPV which in turn is part of the company's overhead costs. "Verification method" has a strong relationship with C_P. Depending on which method applied (part verification, MPV or PPV) the C_P will increase or decrease due to necessary time. "Workers", "product complexity", "repair equipment" and "time" are all necessary and have a strong relation to C_R. Further, a complex product takes longer time to repair compared to a less complex product; thus the strong relation to C_R. Here, a complex product denotes a product with many parts (see Cambridge 2003), many functions, difficult assembly- and manufacturing operations. Basically, as told by one of the engineers at the company, a complex product involves many steps that can cause a defect. Also, a complex product increases the probability that defects will occur, P_O. This is confirmed in one of the projects at the studied company in which, among others, the pneumatic system contains many parts and functions. The product was considered more complex than usual and had 212 reported defects in the project, average number of defects is 96 in 15 studied projects. Of the 212 reported defects "wrong way of thinking" and "operator mistake" caused 18% respectively 59% of the defects according to the defect reports.

Further, by analyzing Table 1, defects will be detected by a certain probability depending on the "verification method", number of "workers" involved, and the "product complexity". Therefore these cost drivers have a strong relationship with probability to detect the defects (P_D). "Time" and "verification equipment" have a medium relations on the probability of defect detection. Also, during time pressured projects, workers felt the potential to make more mistakes which relate P_O and time with a 5. Further, it seams easier to detect a defect if more time is allocated for the verifications, thus the medium relation between time and P_D.

The result from mapping the relations is an impact digit. From the impact digits it can be seen which cost driver(s) and factor(s) that has a big impact on the process of detect and repair defects in the assembly. In Table 1, the biggest impact has C_P (30%), followed by C_R (29%), P_D (24%) and P_O (17%). This can be interpreted that, e.g. C_P is more sensitive to changes in the way verifications are performed then P_O; also there may be more to gain from improving the C_P then to focus on the P_O. However, by analyzing the columns of Table 1, it can be seen that "workers", "product complexity" and "time" are the top three with the highest impact digit. These three in turn is the ones that may be analyzed further in order to select the most time and cost effective verification method.

5 Conclusions and Critical Review

It can be concluded that defects seam to still be a variable that needs to be dealt with by companies. However, a modular architecture has shown to be beneficial when dealing with defects; both by detecting the defects and repairing them. These benefits have to do with, among others, the specified architecture and one or few well defined functions in each module. It is therefore believed that verifications should be performed at modular level, so called MPV. The MPV has several benefits which will decrease both time and costs related to defect repair and verifications.

Nevertheless, PPVs, i.e. verifying at product level, may be beneficial if, for example, there are relative few defects that normally occurs. As an approach to measure specific property verifications, a matrix has been described. This matrix maps cost drivers with so called factors with numbered relations. From the matrix, impact digits is summarized both row- and column wise. A company's PPV was used as a pilot case for the matrix in which factors and their cost drivers were mapped. The result from the matrix was that cost to perform (C_P) the verifications has the highest impact digit, and 30% of the summarized relations. This in turn shows that the cost drivers more often have a relation with "cost to perform" than to "cost to repair", "probability to detect" or "probability to occur".

The matrix also shows that the cost drivers "workers", "product complexity" and "time" has the highest impact digits. This in turn indicates that these cost drivers are the ones that most affect the PPV at the company today. Also, improvements in the way verifications are performed may consider these cost drivers since they also affect the cost related to verifications and repair of defects.

The matrix may be used to measure the degree of impact of each factor and cost driver during product verification. This is believed to be useful as an early indication of what is affected in present verifications. The matrix may also be used to compare concepts of verifications with each other, e.g. different approaches to MPV. However, mapping relations with a numbered scale, as in this paper, is always subjective and conclusions drawn from such should be made carefully. Even tough the principle of the matrix seam to be useful, the mapping of the matrix may look different depending on the user. Thus, same user or development team should map all the matrixes, which are to be compared to each other, to avoid different views on the same object.

The work with the development of MPV and how to perform cost and time efficient product verifications will be further developed in forthcoming research.

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