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MODULE PROPERTY VERIFICATION – A CONCEPTUAL FRAMEWORK TO PERFORM PRODUCT VERIFICATIONS AT MODULE LEVEL

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Abstract

This paper presents a conceptual framework for verifying product properties at module level, Module Property Verification (MPV). MPV is an approach to decrease overall lead-times and increase the quality of modularised products. Pre-studies indicate that companies tend to have the majority of property verifications at product level, Product Property Verification (PPV), which may results in increased costs and extended lead-times. At the same time, the implementation of a modularised product assortment brings new challenges to companies such as how to decompose product specifications into module specifications, achieving a balance between properties to verify, designing assembly systems that support MPV, and finding methods to design modules for MPV. The discussions of the proposed conceptual framework constitute a theoretical foundation for MPV based on pre-studies, literature reviews and applicable theories.

Keywords: Modularity and Standardisation, Property verifications, Interface Interactions

1 INTRODUCTION

Modularisation is not a new way of designing products or processes. Almost forty years ago (1964) IBM announced the first modular computer, the System/360 [2]. Companies have, to a varying degree, been able to generate profits due to a modularised product assortment since the System/360. Baldwin and Clark [2] argue that “it is modularity, more than speedy processes and communication or any other technology, that is responsible for the heightened pace of change that managers in the computer industry now face”. They also point out that “strategies based on modularity are the best way to deal with that change”. Pine [9] states that modularisation is the best method for achieving mass customisation while minimising costs and maximising customisation. Customisation through the standardisation of components not only increases variety while reducing costs in manufacturing, it also allows product development to produce new designs with even greater variety, and at a higher pace [9]. Modularisation of the product assortment has also proven to decrease lead-time as a result of parallel activities in module assembly [3], instead of assembling the product part by part on a serial assembly line. Modules can be assembled in separate assembly workshops and supplied to the main flow for the final assembly into a finished product. A decreased lead-time may provide backing for an increase in market share, support an extended sales life, and make higher profit margins achievable due to pricing freedom [11]. Parallel activities require specifications of interfaces which in turn allow parallelism both in product development and manufacturing [12] and, at the same time, concurrent processing of independent modules will reduce the cycling time dramatically. Such advantages overweigh the cost of interface specification.

1.1 Module level verification

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. The verification of properties at product level is called product property verification, PPV. In this paper, verification is defined as *the process of determining whether or not the products at a given phase in the life-cycle fulfil a set of established specifications*. The specifications are derived from the properties (a metric and a value [13]) which the product must embody to fulfil customer needs. In addition, modularisation is defined as *a decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific reasons* [3].

The reasons for performing MPV have been discussed by many authors, for example [3] and [10]. Also, Pimmler and Eppinger [8] point out the advantages of decomposing complex products into multiple sub-functions. These sub-functions are generally easier to handle than the complete product, and the technical solutions to the sub-functions can be developed in parallel. Baldwin and Clark [1] argue: "To evaluate a module without embedding it in a prototype system requires detailed knowledge about what the module contributes to the whole, as well as how different modules interact." The possibility to perform MPV is also discussed in Ulrich and Tung [14]; who say 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".

In *Assembly Initiated Production* (AIP) Karlsson [5] and Onori and Karlsson [7] emphasize the importance of reducing the lead-time by making the customer order immediately available to the assembly workshop. In AIP the only lead-time for the customer will therefore be the final assembly of modules into the demanded product and its shipment. In order to achieve the shortest possible lead-time, (i.e. no more than the time consumed for final assembly and shipment), the properties of every separate module have to be known and verified, as well as the resulting property set of the assembled product. Otherwise, the property verifications have to be performed after assembly, which will extend the lead-time. Consequently, AIP underlines the importance of performing property verifications on module level.

In the literature it is clear that a module product assortment has many benefits. However, modularisation is not fully exploited due to the lack of methods and strategies for companies to follow in order to perform product verifications at module (or sub-assembly) level. The objective with this paper is therefore to present a conceptual framework, from here on called framework, for MPV which includes ensuing challenges and considerations.

2 THE CONCEPT OF MODULE PROPERTY VERIFICATION

It is known that it can be ten times more expensive to repair a defect on a completely assembled product, than it is to the repair the defect at the time it occurs [10]. For some companies this number is of even greater magnitude. Even though, companies still perform the greater part of their property verifications at product level.

One example is ABB Power Technology Products/Components which assembles 1100 high voltage transformer components annually. To ensure that there are absolutely no defects, every component is verified at final assembly, which takes time and money. Another example is Remote Control Sweden AB, which assembles pneumatic, electric and hydraulic valve actuators. Remote Control Sweden AB competes in the global market for high quality products, selling over 25 000 products annually. Quality is assured through several property verifications on all products at part level, sub-assembly level and product level. Dellner Couplers AB, a manufacturer of train couplers, are implementing a modularised product assortment. They verify the couplers by mounting them in a test fixture and applying a required load to simulate conditions between two carriages, Figure 1.

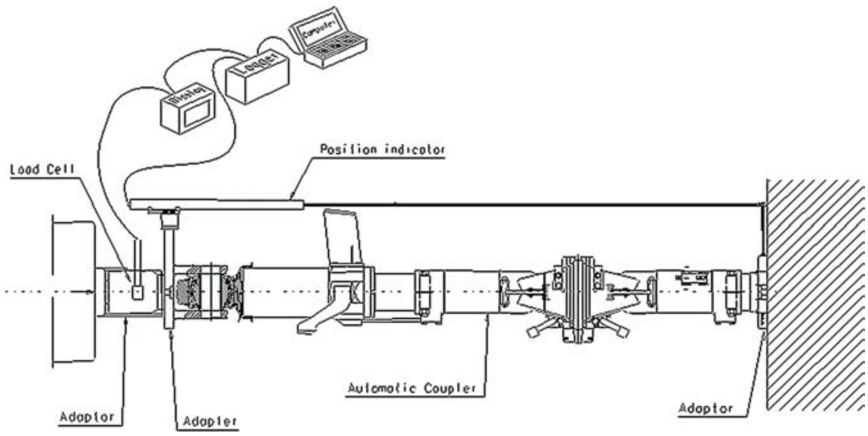

Figure 1: Test set-up for verification of train couplers at Dellner Couplers AB.

Sepson AB, a producer of high quality hydraulic winches for civil and military use, has to disassemble the verified winch after the PPV in order to detect any defects. These examples of property verification are unnecessarily expensive and, furthermore, extend lead-times.

PPV can be summarised 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. As illustrated earlier, it is more difficult and expensive to repair any defects on an already assembled product. In addition, heavy and/or bulky products are difficult to handle during PPV.

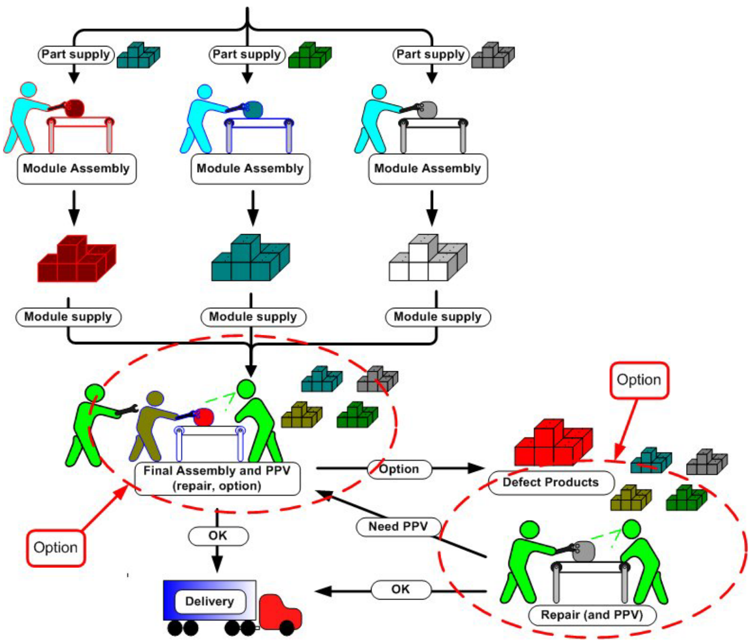

Figure 2: Product property verifications (PPV) at final assembly.

To avoid extended lead-times and increased costs due to PPV, companies can strive to move the product verifications to an earlier stage in the assembly. Preferably the product verifications should take place at module assembly, Figure 3. 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).

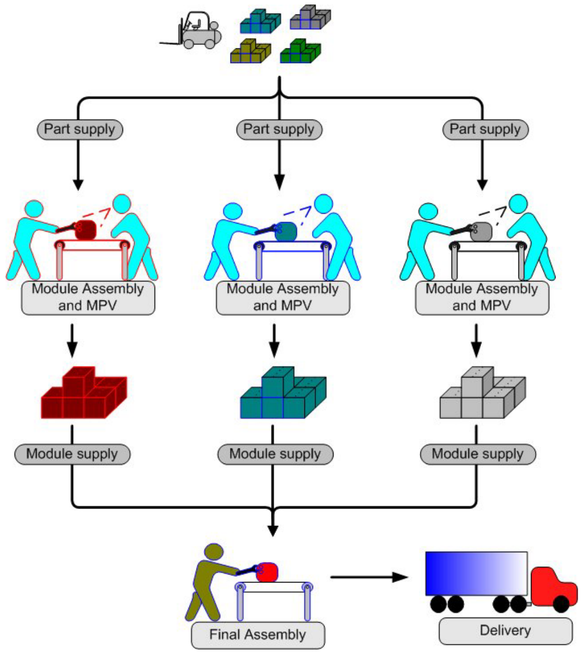

Figure 3: Module property verifications (MPV) at module assembly.

2.1 Challenges with the implementation of a modularised product assortment

The implementation of a modularised assortment confronts companies with new challenges; especially for companies with products which can be considered capital intensive, considering the verification of product properties, and when an MPV approach shall be used. Capital intensive implies that the property verifications are time consuming, expensive, difficult to perform or difficult to evaluate.

Firstly, the challenge is how to decompose the product properties into module properties, and how to derive product properties from verifications at module level. If companies want to increase their profits with the aid of a modularised product assortment, the products and the corresponding properties have to be specified and verified at a module level.

Secondly, the challenge is to find a balance between the properties of the product and what needs to be verified, and to make the right trade-offs suitable for module level verifications. There are a large variety of standards/regulations which have to be fulfilled. At the same time, demands from different customers vary [6]. The engineers performing the verifications have two choices: make trade-offs between the standards and demands from customers in order to make verifications quicker and more economically feasible, or handle all possible standards/regulations and customer demands even if they sometimes overlap, resulting in extended lead-times and increased costs.

Thirdly, the challenge is to verify the module properties separately and to have "separate testability" as a major module driver when the module concepts are designed. Module drivers are a part of the modular function deployment (MFD) method [3] and are company-specific reasons for the development of modular products. One of the module drivers is "separate testability”, which means that if there are any reasons to verify the properties of a module separately it shall be considered during the development of the module.

To facilitate module level verification it is important that the product is designed for this verification, especially if the verifications are capital intensive. One studied company, with a modularised product assortment, has applied “separate testability” as one of the module drivers in 30% of the modules of a product. In the same company, for yet another product, the percentage is 13%. Nevertheless, the company strives for greater module level verification.

The challenges show that the full achievement of modularity advantages can be jeopardised by: excessive verification times for the completed products; the difficulty to derive product properties from module level verifications; not utilising the optimal place for the module verification workshop; and, not designing the module for separate testability.

2.2 Theory of Module Property Verification

MPV may be seen as: *A property verification of modules, corresponding to the breakdown of the product properties into module properties, as an integrated part of a complete assembled product*.

This emphasizes that the property verification should be performed at module level and verified corresponding to the properties of the completely assembled product. The product properties are specified through standards, authorities, customer needs, and internal needs within the company, illustrated in Figure 4.

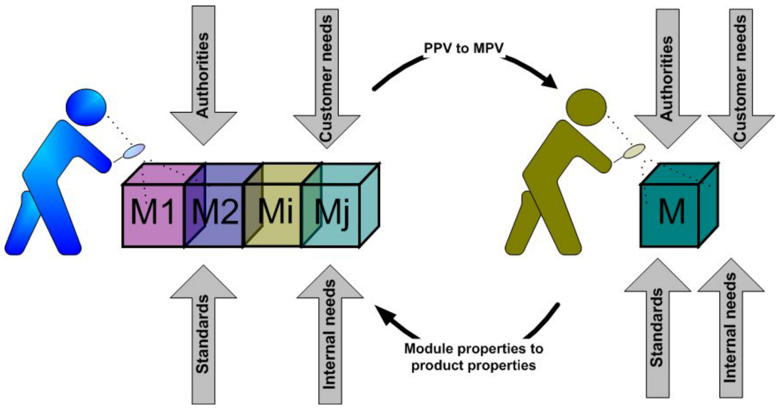

Figure 4: Schematically, a product that is built up by *j* modules and verified at product level (PPV), on the left, and on module level (MPV), on the right. The vertical arrows denote the specifications on the product which have to be decomposed from product level to module level. The verified properties at module level need to be translated back into product properties.

In MPV it is important to have a complete overview of the product assortment, i.e. all possible module combinations for product variants, because the module has to be verified as an integrated part of the assembled product. Different module combinations may demand different properties among the modules building up the product. The following three situations of module products, or a combination of them, should be considered.

- Identical products - the product is completed by assembling modules which have only one variant each
- Variants of products - the product variant is completed by assembling modules that have one or several variants
- Redesign of products - redesigned modules with one or several variants each that complete the redesigned product variant

The interfaces' interaction between modules also has to be considered, as well as the property transformation of the actual module. An interface may be seen as the connecting system created between two modules. Six different interface connections between modules are described by Erixon [3]: Attachment, Transfer, Control and Communication, Spatial, Field, and Environmental. Interface connections can also be looked upon as "property carriers". The property carriers transfer and/or receive properties to and from other modules, and to and from the connecting environment. The transformation through transfer and receive may be described as a model for a modularised product, see Figure 5, where:

- A module transforms and/or forwards received properties, within the *Module System*. For example electrical energy is transformed into kinetic energy, or heat is received from one module and is propagated through a second and forwarded into a third.
- The transformation and/or forwarding of properties results in a transfer and/or receive to and from the module. The transfer and/or receive takes place within the *Modular Product System*. For example, a module with a damping function receives a compressive force of 1000kN from one module, and transfers a compressive force of 400kN to another module, plus heat to other modules as a result of the module's damping capacity.
- Transfer and/or receive also takes place to and from the *Environment System*. The environment system may be seen as the surroundings which affect the modular product system and the module system, e.g. train carriages on both sides of a train coupler, electricity required by a product, or human users.

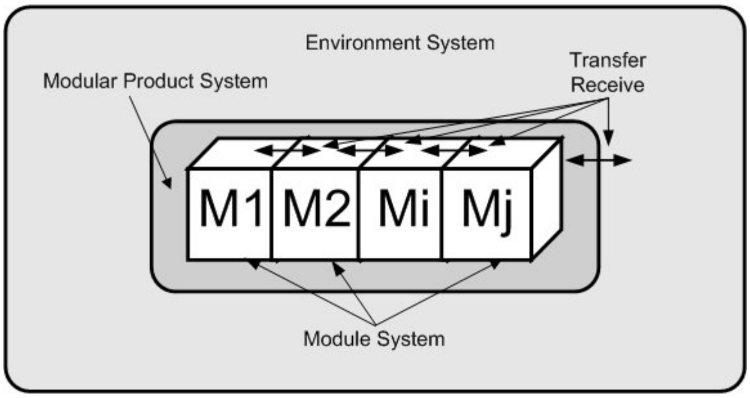

Figure 5: A schematic model of a modular product with different systems, M1, M2, Mi, and Mj denote modules in a product build up by j modules.

The transformation within a module has its origin in hidden design parameters. Hidden design parameters mean that the design parameters of module *Mi* do not affect the other *j* modules, provided that the interfaces are locked and necessary changes take place within the interfaces. Thereby, it may not be necessary to analyse the transforming within a module since it does not affect (or should not affect) the other modules.

On the other hand, the transfer and receive has its origin in visible design rules which cover the parameters which affect the interaction between modules. This includes the architecture (the design of the modules, modules in the product, and the modules' function), and the interfaces (interaction of modules through the different property carriers).

The transfer and/or receive between modules results from the environment system, the modular product system, and the module system. Thus, if the total transfer and receive system is known, the complete product properties are known. In addition, MPV should measure what the modules are capable of transferring and receiving between each other. Based on this, it is postulated that the resulting property of a modularised product is the sum of the receiving (R) and the transferring (T) between the total number of interfaces (Im) (including the interfaces between the environment system and the module product system and module system), equation 1; provided that each module withstands the transfer and receive from all the other modules.

$$\textit{The resulting property of a modularised product} = \sum_{m=1}^{n} R_{\mathrm{Im}} + \sum_{m=1}^{n} T_{\mathrm{Im}} \qquad (1)$$

A modularised product with j modules and n interfaces may have several property carriers which result in a transfer/receive system of properties between all the modules. In Figure 6 interface I_m on the detached module M_i transfers (T) and receives (R) properties to and from interface $I_{n\text{-}IMi}$ on M_{j-1} modules. To overlook modules which do not have obvious interaction with each other may result in unwanted transfer/receive of properties not being detected, causing a defect or disturbance in the overall function. Therefore, this transfer and receive interaction has to be carefully considered.

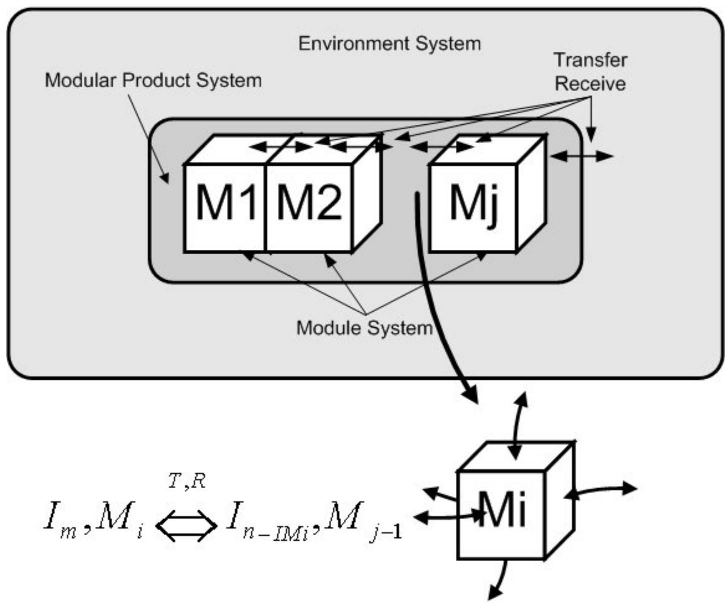

Figure 6: A module (Mi) detached from its context which transfers and receives properties within the modular product system and environment system, schematic.

In Figure 6,

n = maximum number of interfaces (including environment)

j = maximum number of modules

IM_i = all the interfaces on module i

$\Leftrightarrow$ = transferring and receiving of properties.

A similar approach has been proposed by Hubka and Eder [4] using the *operand* concept instead of Environment System, *transformation* process instead of Module System and *receptors* and *effectors* instead of transfer and receive. These authors, however, do not apply the approach in the context of modular products and MPV.

2.3 A framework to perform MPV

In this section, a 9-step framework for MPV is explained, Figure 7. This framework is based on pre-studies in four different companies and the discussions in this paper.

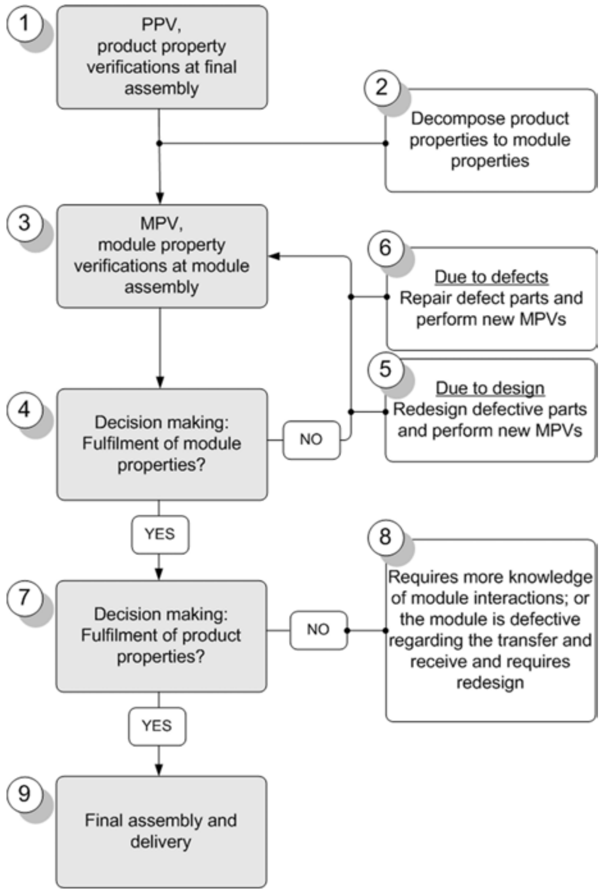

Figure 7: A framework for module property verifications (MPV).

Step 1: The framework starts from a complete product and its properties in order to have a contextual overview. As discussed in relation to Figure 2, to perform PPV can be costly and may extend the lead-time to customer. The company should strive to move the property verifications to an earlier stage in assembly.

Step 2: In order to verify the properties at module level, the product properties need to be decomposed to module level as shown and discussed in relation to Figure 4.

Step3: The verifications of the products take place using a MPV approach, discussed in relation to Figure 3. It is proposed that the verification should measure what the module is capable of transferring and receiving, discussed in relation to Figure 5.

Step 4: After the MPV, a decision has to be made, i.e. does the module fulfil its specified properties?

Step 5: If any design related defects are detected, the module's defective part is redesigned to withstand specified properties. Since a module assortment conveys the possibility to have parallel module design teams, a redesign of parts in a module should not affect the design, manufacturing or assembly of other modules. Thus, defects should preferably be detected at module level. When the defect part is redesigned and manufactured, a new MPV is performed according to *Step 3*.

Step 6: If any defects are detected, which depends on defect parts, spare parts, as well as necessary assembly tools, are made available in the module assembly workshop. When the defective part has been repaired, a new MPV is performed according to *Step 3*.

Step 7: When the modules have fulfilled the specified properties, a new decision has to be made, i.e. are the product properties fulfilled? This requires knowledge of each module's contribution to the overall product as discussed in relation to Figure 6. In this paper, it is postulated that when each module's contribution of transfer and receive is known, the complete product property is known, equation 1; provided that each module is not defective regarding the transfer and receive to and from all the other modules.

Step 8: If the module properties together do not fulfil the specified product properties, it may depend on either insufficient knowledge of the transfer and receive, and more careful study of each module contribution to the complete product is necessary, or that the modules are defective regarding the transfer and receive, and redesign is required before the module re-enters the framework at *Step 3*.

Step 9: The final step, in which the product is verified at module level and each module's contribution to the complete product is known, which fulfils the specified product properties. The modules are assembled into a complete product and shipped to the customer, or put into stock.

3 SUMMARY

Modular product assortment renders companies more competitive due to, among other things, reduced cost risks and reduction of the lead-time due to parallel activities in design, manufacturing and assembly. Since a module has, or should have, specified interfaces and properties, it is possible to perform product verifications at a module level. This verification is called module property verification, MPV. Pre-studies in industry indicate that the majority of the verifications are performed at a product level, called product property verification, PPV. However, such PPV extends the lead-time to customer and may increase the cost to repair defect products by, at least, magnitudes of ten times the cost to repair the defects as they occur. Companies can enhance the benefits from a modularised product assortment by performing the property verifications with an MPV approach. However, strategies and methods to follow are not to be found in the literature. Therefore, a conceptual framework for MPV with 9 steps has been proposed and explained. This conceptual framework describes steps which companies need to take or consider when going from verifications at product level (PPV), to verifications at module level (MPV). The conceptual framework should be a support for companies to reach the full achievement of modularity. Within the conceptual framework, it is proposed that the MPV should measure how each module contributes to the complete product, in terms of transfer and receive effects to and from all modules. A model for a modular product is used to illustrate these effects, including three different systems; environment, modular product and module. The conceptual framework will be further elaborated into an applicable method in ongoing research at Dalarna University, Sweden and at the Royal Institute of Technology, Sweden.

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