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Modular Design Method for Reconfigurable Manufacturing Systems

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Abstract

Reconfigurable manufacturing systems (RMS) have the potential to reduce investments, time-to-market, and cost of variety in increasingly complex markets. However, tools to support the transition in industry are lacking. One enabler of RMS is modularity, however few methods support the design of modular manufacturing systems, and even fewer modular RMS. This research proposes an adaption of the Modular Function Deployment method to address this issue, and also identifies a number of additional module drivers which are relevant to support the modularization process of RMS.

Keywords: Modularity; Manufacturing system architecture; modular function deployment

1. Introduction

Reconfigurable manufacturing systems (RMS), first coined by Koren [1], is a class of manufacturing systems which are capable of efficiently and quickly adapting to changes in the market, such as changes in demand, product mix, or introduction of new product variants. Several studies have investigated how RMS can benefit manufacturers in terms of operations as well as new product introductions. The specific benefits from implementing RMS as well as the specific methods for developing it and the enablers, and how they are physically implementer however depends heavily on the context. This context can relate to competences in the company, the actual change drivers, product characteristics, product characteristics etc. According to the early works on RMS, reconfigurability has several enablers, of which the most important are modularity, integrability, customization, convertibility and diagnosability [2-4]. Even though RMS has a significant value proposition, and several case studies indicate great potentials, and implementations confirm this, RMS is seeing little adoption in industry. This can be explained with various reasons, however one significant reason for this seems to be the lack of methods supporting the actual development of the reconfigurable manufacturing systems, as they require a somewhat different approach compared to traditional manufacturing systems.

The changes in capacity or function, accommodating the need for change is implemented in RMS by adding, removing, or replacing system elements, i.e. modules in the manufacturing system. This implies that modularity is an enabler that is seen in every implementation of RMS in some way or another. Modularity however can take many forms and be realized using a variety of different methods.

Modularity refers to a specific property of an architecture of a system, in this context either a product or a manufacturing system; whether the elements of the system can be considered modules. Modularity has a multitude of definitions in academic and practice-oriented literature; however most definitions are variations of a clear relation between functions and physical elements, and clearly defined interfaces [5].

In product development, product modularity implies that the product is partitioned into a number of physical elements,

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modules, which each implements one or more clearly defined functions in the product. The modules have clearly defined interfaces, which implies that modules can be developed and manufactured separately. This may benefit in a number of different ways, e.g. supporting variety by combining modules in different ways, supporting standardization by reusing a standard module across different products, increasing development speed as new product can be introduced by developing only one new module combined with existing modules etc. Ericsson & Erixon. provided a list of these benefits, referred to as module drivers, since these benefits would drive modularization. It may be possible to achieve several of these benefits for the same module or product, but in some cases the benefits are mutually exclusive, such as standardization vs. variety, and product developers must prioritize and choose which expected modularity benefits to design for.

As mentioned above, modularity has also been applied in the design of manufacturing systems, although by far it is more commonly applied in the product domain. In manufacturing, modularity can be applied on various levels. On tool modularity can allow for example for one tool to be used for multiple components by replacing parts of the tool [6,7]. On systems level, modularity can allow for introduction of entirely new products by replacing or adding new cells or workstations with new functions [8,9].

Designing modular systems remains a challenging task no matter the domain, and this has consequently been subject to much research proposing a plethora of methods for designing these. Most research seems to have been focused on the design of modular products and less research on modular manufacturing systems.

One method which is often applied in modular design is the design structure matrix, DSM, which clusters elements based on their technical constraints or interaction, i.e. interfaces, thus forming module candidates [10]. DSM by default however does not prescribe how to identify nor prioritize these constraints. Ulrich and Eppinger proposed a modular product design method which relies on iteratively combining functions or physical elements into clusters and qualitatively evaluating the performance [5]. This approach however requires prior knowledge of what may be beneficial to combine in a module and does not provide guidance in this process.

Previous works have presented approaches which integrate MFD and DSM, however the specifics are sparsely described, and the MFD is seemingly used as is without adaption to the manufacturing domain [11].

Previous work has addressed the issue of applying MFD to the manufacturing domain, and evaluated which module drivers from the original method would be applicable to manufacturing systems [12]. This research however did not identify additional driver nor proposed a method for incorporating them into modular manufacturing systems design. This was done by Rossi et al. [13] who also combined MFD and DSM to establish a method for developing a modular architecture of a production plant. This method however was applied for a process plant and requires adaption for discrete manufacturing. Furthermore, it involves a highly complex process with 35 steps which may be overwhelming for some companies in the early design phase of a manufacturing system. The MFD method however does however provide a structured approach to developing a modular product architecture, and is by itself a rather simple tool that may prove useful when initially developing modular manufacturing systems if adapted.

The objective of this research is to propose a method based on the MFD approach which supports development of a modular architecture supporting reconfigurable manufacturing, also considering adapted module drivers.

In the following section, the original MFD method, intended for product modularization, will be briefly outlined to form the basis of the adaption to the manufacturing domain.

2. Modular Function Deployment

The MFD methods in its original form consists of five steps, connecting customer requirements to optimized modules in a product design through a guided process [14]:
Step 1: Define customer requirements: In this step the customer requirements are clarified and linked to technical specifications. This is typically done through a QFD matrix, which is a well proven tool to do this [15]. Step 2: Select technical solutions: In this step, the functions identified in step 1 are translated to technical solutions. This is done by functional decomposition, by e.g. applying a function means modelling technique. So far, the MFD method does not directly address modularity issues, and the process could just as well be applied in any product development project regardless of modularity objectives. Step 3: Generate module concept: This is where the MFD method significantly differs from other product development processes, and where the key to establishing the modular architecture is found. In this step, a matrix is generated in which the relations between module drivers and technical solutions, found in step 2, are evaluated. The module drivers are as mentioned in section 1, potential benefits that may be achieved by partitioning certain functions into one physical module. Doing the module indication matrix then guides system developers to evaluate which drivers are more important for each function. This is done much similar to how a QFD matrix is performed, and is illustrated in figure 1. In this example, four functions are rated in terms of how relevant each module driver is. This is done on a scale from 1-9, where there can either be no relevance, a weak relevance, 1 point, medium relevance, 3 points, or strong relevance, 9 points. For each function the scores are added, and the functions that get higher scores are module candidates. Functions with lower scores can be combined into the module candidates to form modules. However, only functions that have similar module drivers should be combined. In figure 1, functions a and b would be module candidates as they have the highest scores. Function d could then be integrated in a module with function c, since the have similar module drivers, and no contradiction module drivers. On the contrary, combining functions b and c would not be beneficial, since the have relevance in relation to “Different Specification” and “Common unit”, which are contradiction, since it implies either standardization or increased variety.

Step 4: Evaluate module concept: In this step the architecture is evaluated in terms of interfaces, which has implication in relation to assembly sequence. Also, in this step financial evaluations should be made to compare different alternatives of module concepts, or comparison to an existing product design. Step 5: Optimize modules: After step 4, modules are set and interfaces are specified, and in step 5 modules are optimized internally, satisfying the interface specifications.

	Module driver	Function a	Function b	Function c	Function D
Development and design	Carryover	9			
	Technology evolution		3		3
	planned design changes			9	1
Variance	Different specification		3		
	Styling				
Manufacturing	Common unit	9		3	1
	Process/organisation				
Quality	Separate testability		1		
Purchase	Supplier availability	9		9	
After sales	Service/maintenance				3
	Upgrading				
	Recycling		3		
	Sum	27	10	21	8
Strong module driver - 9 points		9			
Medium module driver - 3 points		3			
Weak module driver - 1 point		1			

Figure 1: Example of module indication matrix from the modular function deployment method

3. Research Methodology

The approach to establish an adapted MFD method for simple application in manufacturing is divided in two parts. One part is adapting the procedure, since developing manufacturing systems by nature is different from developing products. The procedure was adapted by iteratively making experiments applying the originally proposed procedure for products in the manufacturing domain, and altering it for the cases where it does not apply, however addressing the intended aim of each step. The other part is adapting the module drivers to general manufacturing. The module original drivers from Erixon [14] are not all expected to be relevant [12], and additional drivers might be relevant. For identification of module drivers for manufacturing systems a literature review has been conducted searching for drivers explicitly referred to as module drivers, as well as other potential benefits expected from modularity in manufacturing systems. All of these were consolidated by formulating an ontology to avoid redundancy in drivers. In section 4, the procedure is outlined, and in section 5, the module drivers are described.

4. Method proposal

In this section, each step from the original MFD procedure is evaluated and adaptions are proposed where relevant.

Step 1: Define customer requirements: Since customer requirements are design input for products rather than manufacturing systems, this step is not directly applicable to manufacturing system design. Rather than using a QFD matrix to translate customer requirements into technical specification, a QFD matrix may be used to translate manufacturing system requirements, in terms of e.g. processes and demand characteristics, into technical specifications. However, this requires identifying the right requirements as well as specification, and hence a method employing more guidance may be beneficial. Such method is presented by Andersen et al. [16] specifically focusing on capturing requirements for reconfigurable manufacturing in terms of product variety, mix, demand, and uncertainty.

Step 2: Select technical solutions: In this step different technical solutions are evaluated and selected. In the original method, Erixon proposes using a function means modelling tool to systematically evaluate different alternative technologies. This may very well also be applied in manufacturing systems, as this method is generic to all systems engineering. However, adhering on the concept of co-platforming [17], where the development of the product portfolio and the manufacturing system portfolio are closely related, it seems beneficial to formalize the description of the relations between products and processes in a company. An approach for this is proposed by Brunoe et al. [18], which would support the process of doing selecting the technical solutions.

Step 3: Generate module concept: Being the core in the MFD method, this step is considered applicable one to one. The only modification necessary would be adapting the module drivers, since module drivers for manufacturing differ significantly from module drivers for products. These module drivers are outlined in section 5. This step is critical towards obtaining useful results in practice, since the step implies rating the importance of module drivers to each technical solution. Each rating is decided upon by domain experts, and as such there is no right or wrong answer, but rather a subjective judgement. Similar to performing a QFD process, the output should not be considered a locked design specification, but rather a structured way of incorporating relevant perspectives into deciding on the architecture of a system. Though the MFD does provide a structured approach is it rarely used an exclusive tool to define a product architecture but rather a guide for incorporating relevant considerations in the process.

Step 4: Evaluate module concept: The original MFD method focused primarily on evaluating interfaces and assembly sequence in this step. This is less relevant in terms of manufacturing systems, since a manufacturing system is assembled only once, implying much less impact on financial performance than the ease of assembly for products. For manufacturing systems, evaluating the module concepts much take a full cost, life cycle perspective, evaluating the impact from different module concepts on the investment cost and operating cost. Such method is proposed by Andersen et al.

[19], specifically reconfigurable manufacturing, which would be suggested to use for evaluation in this context.

Step 5: Optimize modules: This step focuses on the development of the modules, once the interfaces have been chosen. Being very context dependent, the original method also does not provide much guidance on this, except suggesting that the module drivers indicated relevant in the module indication matrix should be an internal design requirement for the modules in this step, which would also be the case in manufacturing systems.

5. Revised Module Drivers

To apply the adapted MFD method outlined in section 4, a collection of drivers for modularization of production systems and equipment must be defined. These drivers are used for Step 3: generate module concept. The module drivers have been identified and defined as a result of a consolidation effort from a literature review on module drivers, with a point of departure in the original MFD as presented by Ericsson & Erixon [14] and additional drivers and definitions from supporting literature [5,12,13].

In total, 17 module drivers have been identified, and defined in relation to production modularization. All 17 drivers are listed in Table 1. They have been grouped into five categories, shown in italics in the table. The module drivers are grouped based on when and how in a system's life cycle they primarily provide an advantage. Some categories were initially module drivers themselves but have been raised to category level.

Module drivers in the *localization of changes* category are intended to develop modules for limiting the propagation of change. By isolating functions or equipment that expected to change in modules, once the change occurs (e.g. through technology evolution or new regulations), it should only affect the specific module in which the change occurs, having minimal effect on other modules and the rest of the system. Isolating expected changes to modules further facilitates development of standardized modules which can reused across coming generations of the system. Using drivers in this category may help reduce development costs for new systems, and accelerate development and introduction of new technologies, while increasing system robustness. One example is a production cell or station using a technology which the company is ready to replace with a newer technology, e.g. transitioning from arc to laser welding.

In the *managing variety* category, module drivers focus on creating the necessary variants of a production system, required to manufacture the relevant products at the desired rate. Module drivers in this category seek to create standardized modules that can be used across a range of manufacturing systems within a manufacturing segment or factory (i.e. common unit). Other modules are then designed to carry out specific functionality, unique to a given system, or to provide a system with a certain degree of changeability, e.g. modules allowing production volume to be scaled up or down if needed. Using these types of modules can accelerate development and reduce costs related to new systems. For instance, modules designed from commonly used processes or tools, forming a platform to build future production systems on, e.g. a specific way to transport and identify work-in-progress using pallets and conveyors.

The *system development* category constitutes module drivers intended to create modules making development easier by standardizing (1) interfaces, (2) the way in which components with shared subfunctions are designed, or (3) precision and integration between components is ensured. These modules can help balance overall system and module complexity by integrating multiple functions into one module, or splitting them up across multiple modules. For example, equipment used for multiple operations in one cell, such as a welding cell using one robot and two different fixtures.

Module drivers making up the *in-use* category, seek to develop modules based on how a production system and its constituent parts can be treated and maintained while in its serviceable phase, and once it is nearing the end of its life. The

Table 1: List of identified module drivers for production modularization. Rows in italics represent categories. Numbers in brackets represent the reference where a driver or category has originated from or been inspired by.

Driver	Description
Localization of Changes [3,10]	*Modules for limiting propagation of change throughout a system's lifetime*
Module Carryover [10-12]	Equipment unlikely to change over coming generations of the system
Planned System Changes [10, 12]	Equipment with planned design changes
Technology Evolution [10-12]	Equipment using underlying technology either new or likely to change
Regulation & Standards [11]	Equipment subject to certain external regulations and standards, which might incur changes
Managing Variety	*Modules for managing and creating necessary variants of manufacturing systems*
Common Unit [3,11,12,16]	Equipment common to a manufacturing segment
Different Specification [3,10,12]	Equipment creating variety in a manufacturing segment
Changeability [11]	Equipment with similar type and range of changeability
System Development [10]	*Modules implementing functions and interfaces*
Function Sharing [3,10]	Equipment sharing subfunctions
Geometric Integration & Precision [3,10]	Equipment with requirements for physical alignment in relation to each other
Portability of Interfaces [3,10]	Equipment relying on interactions and interfaces with similar portability
In use	*Modules related to how a system is handled when it's in use*
Service & Maintenance [10-12]	Equipment with similar service and maintenance intervals and/or tasks
Recycling [10-12]	Equipment handled similarly during end-of-life
Customer Requirements [11]	Equipment creating variations in system configuration/performance but not forming new variants
Upgrade [12]	Equipment replaceable by end-user for changed functionality or features
Process and/or Organization [3,12]	Equipment implementing processes always carried out in sequence
Procurement [3,10,12]	*Modules easing production and procurement of manufacturing equipment*
Vendor Capabilities [3,10,12]	Equipment sourceable from individual suppliers/vendors
Separate Testing [10-12]	Equipment requiring specific types of tests or separate tests

module drivers in this category have a variety of goals, like increasing predictability and longevity of equipment in terms of service and maintenance, and gradually upgraded capability. They also deal with easing the recycling process by reducing the amount of different materials in modules, and organizing processes or equipment according in relation to each other to reduce the overall system complexity.

In the final category, *procurement*, module drivers related to the procurement of production modules are grouped. These module drivers aim for modules easing the procurement process, e.g. by modularizing critical equipment or functions that should be tested separately from the rest of the equipment, or equipment that require similar testing. Developing modules for this purpose, as well as modules aimed directly at the capabilities of the vendors, can reduce the costs and time of development, and the costs related to test/run-in of purchased equipment. These modules could be equipment or tools performing processes that are not considered critical for the company to develop in-house, and can thus be outsourced to vendors, who may already have standardized solutions.

6. Conclusion

This research has proposed a simple structured approach to establish a modular architecture for a manufacturing system. Whereas previous methods for this assume are either aimed at product modularity, or being very specific for certain process type in manufacturing, or very complex in use, this proposed method is intended to be simple in use, yet provide specific prescriptions on establishing an architecture. The method is an adaption of the modular function deployment method from Erixon & Ericsson [14], which was originally intended for developing modular product architectures in five steps, based on prioritization of module drivers and analyzing their relations to technical elements in the system. This research has provided alternative, and additional methods to be used in each step, and proposed an adapted set of module drivers, as the original module drivers were suitable for products rather than manufacturing systems. This research is limited in just proposing a method, and thus no empirical validation of the approach has been performed at this point; this would be subject to further research. The authors of this paper are currently involved in an industrial research project bridging the gap between research and industry on RMS design methods, and this method is currently being validated in two different companies. In these companies, the method is being applied in already running production system development projects on real manufacturing systems, providing input for the production engineers while validating the method.

Practical implications of this work would be enabling manufacturing system engineers and managers to more rapidly, and with higher confidence include different criteria into the modularization process when designing manufacturing systems. As mentioned in the introduction, modularity in manufacturing systems is an essential enabler for reconfigurability, and this method would provide a means to incorporate different requirements related to reconfigurability into the modularization process and weigh them against other criteria as described in the module drivers.

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