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Application of module drivers creating modular manufacturing equipment enabling changeability

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Abstract

The changeability of manufacturing systems can be of great importance for manufacturing companies to react rapidly and cost-effectively to market and product changes. Creating the basis for increasing the reuse and reusability of the manufacturing system then becomes critical since such capabilities would minimize the cost and/or investments that traditionally follows NPI projects and/or generally handling product variety. To accomplish the changeability of a manufacturing system one important enabler is modularity, which facilitates reusability. The basic concepts of modularity and platform architectures applied in product development can often be directly transferred to a production context though it does not necessarily imply that methods introduced as generic product modularization methods can be adopted directly with the purpose of developing modularized manufacturing systems. However, this paper adopts a method from product development literature to identify the optimal modular structure. Thus, this paper provides a methodology to apply module drivers in the design of modular manufacturing equipment, demonstrated on an industrial example.

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Keywords: Module drivers; Modular manufacturing equipment; changeability

1. Introduction

The dynamics of today's global markets forces manufacturing companies to respond rapidly on the challenges that follows a demand for higher product variety and shortened product life cycles to compete [1]. Thus, capabilities to adapt to new system functionality and change capacity in order to introduce new products and ramping up production efficiently becomes important prerequisites to compete [2]. Creating the basis for increasing the reuse and reusability of the manufacturing system then becomes critical since such capabilities would minimize the cost and/or investments that traditionally follows NPI projects and/or generally handling product variety.

Traditionally manufacturing systems as the Flexible Manufactirng System (FMS) and the Dedicated Manufacturing System (DMS) is unsuitable to meet the requirements imposed by the global competitive market. Though the FMS enables high flexibility with its general-purpose machines, it combines low throughput with high equipment cost which makes the cost per part relatively high [2]. Likewise, the DMS has its boundaries since such systems needs to operate at high capacity to be cost effective [2]. A cost effective response to market changes is the Reconfigurable Manufacturing System (RMS), which combines the high throughput of DMS with the flexibility of FMS and is capable of rapidly adapt to new functionality and change the system capacity [2].

To accomplish the changeability of a reconfigurable manufacturing system one important enabler is process modularity, which facilitates reusability of a manufacturing system on different manufacturing system levels [3]. Applying modules has a long history in product development literature and methods can potentially be adopted for production system development purposes. Product family architectures integrating product modules and product platforms are applied for product variants planning purposes [4]. The aim is to achieve economy of scope by delaying product variety differentiation, capitalizing on commonality [5], and is

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motivated by an economic benefit that have been known for several decades [3]. These concepts of modularity and platform architectures has been adopted for manufacturing systems to cope with change and variety in current and future generations of products, and thereby to build adaptability into the manufacturing system.

It is generally accepted that products and manufacturing systems has to be co-developed so that the production system supports both the modular product structure and the production platforms, however the realization is not straightforward and uncomplicated. Such integrated platform development approaches [6, 7] exemplifies attempts to realize holistic platform strategies creating practical approaches to achieve product and production designs [8]. For instance, Michaelis [9] introduces the term Platform-based Co-development of Product and Production Systems similar to research on Co-evolution of Product, Process, and Production Systems [10, 11]. The latter also uses the term Process Platforms and can be seen as the evolution of cellular manufacturing, focusing on product family design and design of its production processes simultaneously [3, 12-14].

The basic concepts of modularity and platform architectures applied in product development can be directly transferred to a production context. However, that does not necessarily imply that methods introduced as generic product modularization methods can be adopted directly with the purpose of developing modularized manufacturing systems [15].

1.1. Research question and related work

To identify the optimal modular structure, different criteria for performing the modularization must be considered [16-18]. In regards to product development these criteria is referred to as modular drivers [17]. As mentioned in Brunoe et al. [19] considering such criteria is of paramount importance when modularizing a production system or establishing a production platform. Brunoe et al. provides a systematic exploration of production platform drivers adopted from product development literature. These module drivers are primarily defined based on the work of Ulrich and Eppinger [18] and Ericsson and Erixon [16], and it is demonstrated by examples that these drivers can be applied on varies manufacturing system levels. However, applying modular drivers for development of modular manufacturing equipment have not been carried out before to our knowledge.

It is well known that Design Structuring Matrixes (DMS) is a well proven tool to express system elements and develop their modular structure, and the ultimate goal of processing a component-based DSM is to cluster system components into modules [20, 21]. However, optimizing these clusters is either constrained by a predetermined number of clusters, number of components per cluster, or geometric properties [21]. Thus DSMs does not provide the information of how those clusters are arranged with respect to each other in the system architecture. To accommodate this, AlGeddawy and ElMaraghy [22] introduced Cladistics with the purpose of grouping components into clusters and to establish a hierarchical structure relating these components, and thereby to identify the optimal granularity level. Thus, Cladistics is also an attempt to optimize component clusters within a system architecture.

Applying modular drivers optimizing clusters of components within the system architecture is not a substitute to DSM and the Cladistics analysis but rather a supplementary decision tool.

Thus, the research question is as follows: *How can module drivers be applied to design modular manufacturing equipment?*

2. Methodology

This paper presents a methodology for modularizing the design of a variety of manufacturing equipment. The methodology is carried out on an industrial example with the purpose of making the fixtures more variant-oriented and to improve the design of a capital intensive process by standardizing modules. The method is carried out based on six different welding fixtures capable of handling 12 different sub-assemblies in a tack welding process. The immediate motivation to implement modularity across these fixtures is the influence of equipment variety on time and resource usage in terms of: 1) changeovers and retrieving of equipment, 2) storing capacity, 3) NPI, including design, manufacturing and installing equipment, and 4) Equipment investments. Therefore, the existing dedicated fixtures is converted into a modular system that can quickly change functionality (i.e. be reconfigured by changing modules) to accommodate a variety of product parts, instead of changing the entire fixture. The objective of the methodology is to derive and convert fixture functions into a number of strongly connected modules such that one or more of them can be changed when needed. By mapping functions across all fixtures change of modules to accommodate part changes are minimized because modules that remain unchanged and modules that might change is identified.

The presented methodology has three main activities as indicated below. The methodology applied is greatly inspired by the backbone literature and the related work introduced in section 1, and additionally research focused on development of modular and platform based production system architectures [23]. However, especially the Modular Function Deployment method by Ericsson and Erixon [16] has been a great source of inspiration deriving modules based on modular drivers and therefore partly adopted for this application in step three.

1. Domain analysis
2. Identify functions and means
3. Derive modules by use of module drivers

1) The scope of production platform development is based on a demarcation of a product domain. Deciding on the area of focus can be based on Group Technology trying to identify and capitalize on commonality across parts/products and manufacturing equipment. Reuse and reuseability is the foundation of handling variety and as parts/products evolve over time the boundaries of part/product families is affected as well, why co-development considerations of product variants and their manufacturing system is of crucial importance

scoping the domain for changeable manufacturing equipment. Furthermore, the investment cost should also be considered when deciding the range of parts the equipment in focus should be able to handle. Thus, different possible solution (i.e. levels of flexibility and investment cost) calls for considering the trade-off between flexibility/reconfigurability and the investment.

2) The domain analysis will have a strong influence on the amount of functionality that needs to be transferred into the future solution. Focusing on functions opens for a more technical view, which is needed to proceed with the design. By analyzing every task throughout the process for every part/product within the scope it is possible to derive applied functions and the means to realize these functions. The outcome is a set of means that can be translated into a set of generic modules.

3) However, it should be assessed whether the temporary grouping of generic functions (i.e. initially assumed modules) should be basis for future modules. The reasons for forming modules will in this step be assesed based on a set of criteria. These criteria is a number of Module Drivers adopted from [19], which is production platform drivers inspired by product development literature [16, 18]. Each of the generic function is assessed against these module drivers in the Module Indication Matrix (MIM) [16]. A number of module candidates are chosen by means of pattern recognition in the matrix based on the relation between the generic functions and the module drivers. Some generic function might have less importance why the possibility for integration with other module candidates arises.

3. Results

3.1. Domain analysis

This particular example takes its outset in a group of parts which differs on a number of product and production characteristics. This domain covers twelve different parts handled by use of six different fixtures. The domain is derived

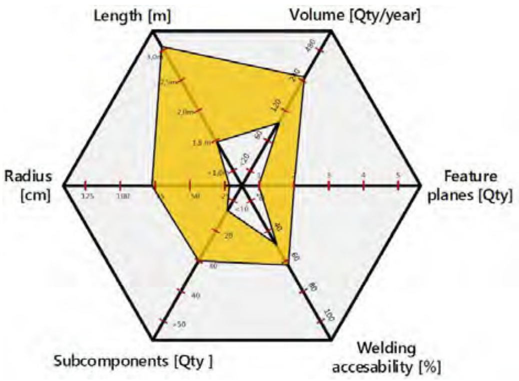

Figure 2 Grouping parts based on product and production characteristics

from a group of parts that is subject to the same routing and by further dividing these parts based on product and production characteristics they ended up being divided into four part domains. The characteristics of the domain applied for this example is illustrated in Figure 1. The characteristics applied in this example arises out of several investigations and interviews trying to identify which characteristics that is important to capitalize on commonality and standardize across a much larger part variety. The nature of the parts included is heavily influenced by their legacy, and thereby the design is based on different principles, which also have had influence on the previous design of the manufacturing equipment.

3.2. Identify functions and means

Previous designs is influenced by insufficient co-development of product and production systems, and lacks in

Table 1 Deriving generic modules by use of function / means matrix across six different fixtures. X's represents a relation between a fixture and the applied function.

Part 1		X	X	X				X		
Part 2	X	X	X	X	X	X	X	X		
Part 3	X	X	X	X		X		X		
Part 4	X	X	X	X	X	X		X	X	X
Part 5		X	X	X	X	X		X	X	X
Part 6		X	X	X				X		
Functions	Adapt fixation distance	Positioning of side plate	Positioning of side plate	Positioning of bottom plate	Positioning of backings	Positioning of front plate	Adapt distance - side plates	Positioning of top plate 1	Positioning of top plate 2	Positioning of support plate
Means	Slider adjusting distance between axle support (14)	Front / back axle support (6,7), side support (9,10)	Front / back axle support (6,7), side support (9,10)	Bottom / top support (8,11), end stop / end support (12)	Separate template	End stop / end support (12)	Top spacer (13)	Side /top support (9,10,11), end stop / end support (12)	Side /top support (9,10,11), end stop / end support (12)	No fixation above center console

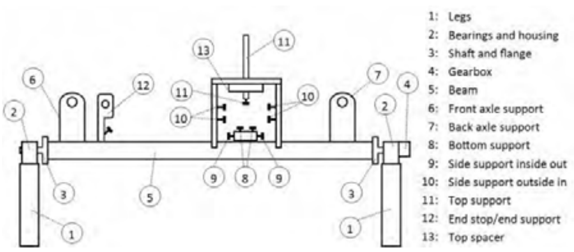

Figure 1 The modules of the initial concept is illustrated and assigned a number based on functions and thereby means represented above in Table 1

terms of platforms prepared for future part introductions. Therefore, the parameters that the derived functions is varying across opens for the evaluation of where or whether extra functionality is necessary to handle future part introductions. This should be considered for each of the future modules when a definitive choice of design is made. By analyzing activities carried out to produce each of the involved parts on the current fixtures generic functions have been derived (see Table 1 and Figure 2). Inspired by current design solutions these functions have been translated into a number of generic means that realizes the functions. Ignoring the sequence of process activities and focus on the relation between generic functions and the functions needed to produce each of these parts a pattern show of which functions is common and which one is unique. Common functions might call for a flexible solution incorporating all the functionality to handle all parts by related means if possible. If not, a reconfigurable solution should be applied and an appropriate granularity level for reconfigurations should be assessed. However, functions that is less representative might call for integration whit other modules or a reconfigurable solution. Current modules is illustrated in Figure 2. However, some modules is not directly interfacing with the product and have therefore not been derived from the initial analysis like the rest of the functions, i.e. current modules. These lower level functions is also represented, i.e. module one to five in Figure 2.

3.3. Derive modules by use of module drivers

Table 2 is illustrating the relation between module drivers and current modules. Based on this, current modules is divided into four clusters as the module drivers is expected to have different importance (i.e. strong or weak relation) to the modules. This provides an indication on whether modules should be further integrated or be divided into smaller modules. The immediate result is five clusters with unique combinations of assigned values representing the importance of each module driver to each of the current modules. This implies that a future fixture solution should consist of five modules. To support this, a binary representation of functional relations between current modules is carried out, which is illustrated in Table 3. Since functional independence is, a wanted feature in a modular system it is possible to indicate which modules that can be clustered based on common functions across current modules. However, representing functional relations does not change the result of the Module Indication Matrix implying five modules. Each of the future modules illustrated in Figure 3 is derived based on different combinations of drivers. The body module is characterized by its high potential for standardization because of its rather low functionality. Furthermore, the body module has a potential for being shared across other part domains than the one this particular example is based on. The beam module is the basis (i.e. base unit principle) on which the other modules is concentrated. Thus, the beam module does not directly manipulate the product parts assembled but provide an interface so that modules that does can be changed to provide new functionality. The axle support module has great importance to the handling operation between the tack welding process and the customer process. Therefore, optimizing this

Table 2 Module Indication Matrix (MIM) adopted from Ericsson et al., relating the module drivers from Brunoe et al. and current modules. Different values are assigned to evaluate the potential for module integration. A high value is equal to a strong relation whereas a low value is equal to a weak relation

	System development			Localization of change			Variety and standardization		Manufacturing equipment	
Current modules	Geometric integration and precision	Function sharing	Portability of interface	Module carryover	Technology evolution	Planned product changes	Common unit	Different specifications	Vendor capabilities	Sum
1	1	9	-	9	1	-	9	1	3	33
2	1	9	-	9	1	-	9	1	3	33
3	1	9	-	9	1	-	9	1	3	33
4	1	9	-	9	1	-	9	1	3	33
5	1	9	9	9	1	3	9	1	1	43
6	9	3	9	3	3	1	3	3	1	35
7	9	3	9	3	3	1	3	3	1	35
8	9	3	3	3	9	1	9	1	1	39
9	9	3	3	3	9	1	9	1	1	39
10	9	3	3	3	9	1	9	1	1	39
11	9	3	3	3	9	1	9	1	1	39
12	9	3	9	1	9	9	1	9	1	51

Table 3 Binary representation of functional relations between current modules

	1	2	3	4	5	6	7	8	9	10	11	12
1		1	1	0	0	0	0	0	0	0	0	0
2	1		1	1	0	0	0	0	0	0	0	0
3	1	1		1	0	0	0	0	0	0	0	0
4	0	1	1		0	0	0	0	0	0	0	0
5	0	0	0	0		0	0	0	0	0	0	0
6	0	0	0	0	0		1	0	0	0	0	0
7	0	0	0	0	0	1		0	0	0	0	0
8	0	0	0	0	0	0	0		1	1	1	0
9	0	0	0	0	0	0	0	1		1	1	0
10	0	0	0	0	0	0	0	1	1		1	0
11	0	0	0	0	0	0	0	1	1	1		0
12	0	0	0	0	0	0	0	0	0	0	0	

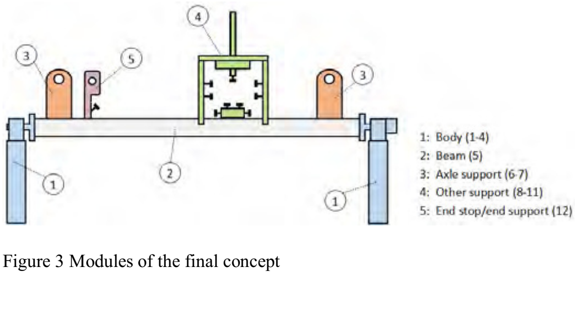

Figure 3 Modules of the final concept

module will imply assessing how this module can be integrated in the manufacturing equipment of the customer process. Regarding module 4 (i.e. other support) it is expected that a layout optimization of the manipulators will provide the opportunity to design a flexible solution able to handle expected variety. Based on the design of the parts assembled in the fixture the end stop module calls for a reconfigurable solution since not all necessary functionality can be implemented in one single module even with further modularization.

4. Discussion and Conclusion

A modularization methodology for modular manufacturing equipment based on product development literature have been suggested. Based on a derivation of manufacturing equipment functions module drivers was applied to modularize these function. The methodology is found to be useful to standardize across a domain with the purpose of modularizing integrated fixturing systems. The methodology was applied to design a new modular concept for a fixturing system that could replace current fixtures to capitalize on commonality. Thus, a new system architecture has been provided, which can adapt to new functionality by changing one or few modules instead of replacing the entire fixture.

Applying modular drivers optimizing clusters of components within the system architecture is not a substitute to DSM and the Cladistics analysis previous applied for modularizing manufacturing equipment but rather a supplementary decision tool. This methodology does not define on which granularity level to reconfigure upon. However, by prioritizing each of the module drivers within each potential future modules is a means to evaluate what is most beneficial for the modularization in each case.

Product variety calls for strategies to cope with related challenges by reducing its effects and maximize its benefits. Modular and changeable solutions are important in order to rapidly adapt to the functionality needed when needed. The introduced methodology exemplifies by use of a case the benefits of modularization of manufacturing equipment.

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