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Brownfield Design of Reconfigurable Manufacturing Architectures: An Application of a Modified MFD to the Capital Goods Industry

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Abstract

Although the concept of Reconfigurable Manufacturing Systems (RMS) has reached its 20th anniversary, it has only grown in relevance. However, the principles are only applied scarcely, although industry recognize the benefits. The transition is limited by a lack of methods which support the practical design of reconfigurable and modular architectures of manufacturing systems and their constituents in brownfield contexts. To address these issues, recent research proposes to modify the Modular Function Deployment (MFD) with a revised set of drivers and tools. Therefore, this paper presents a modified MFD with value-chain considerations and supportive tools, which is validated in an industrial case.

Keywords: Production; Reconfigurability; Modularity; Modularization; Concept

1. Introduction

Although *Reconfigurable Manufacturing Systems* (RMS) has reached its 20th anniversary [1], it has only grown in relevance as manufacturers still face competitive pressure in uncertain contexts [2]. However, the principles are only applied scarcely [3], primarily in the automotive industry where the benefits have been recognized [2, 3]. However, RMS still needs to be explored, and exploited, across industries [3, 4].

One area which is overlooked in research is the design of reconfigurable, and modular, architectures of manufacturing systems in brownfield contexts where conventional methods need to be modified to be applicable [3, 5-9]. This occurs as the systems are complex and context-dependent which complicates the design [4, 5]. A proposed method is the *Modular Function Deployment* (MFD) which has (i) been proved to be applicable across industries with success in the product domain [10-13] and (ii) been researched for applicability in the manufacturing domain [14-17]. Chronologically, the latter has focused on (i) a translation of module drivers to the manufacturing domain [8] which was empirically validated where the authors propose to include *Cladistics Analysis* and *Design Structure Matrix* [16], (ii) a modification of the method to suit the process industry which needs to be modified in a discrete context [15], and (iii) an expansion of drivers which needs empirical validation [17]. In addition to these gaps, some of the drivers reported in the extant literature on MFD in the product domain [10-12] were left out from the ones conceptualized for the manufacturing domain [14-17]. These drivers stem from actors across the value chain which are involved with the product throughout development until end-of-life e.g., manufacturing, transport etc. These are also relevant in the manufacturing domain, as the feasibility of the system architecture depends on the degree to which the imposed requirements and constraints of the value chain are met. This consideration falls across two research domains (i) co-development, which lacks attention from research [2, 9] and (ii) research of RMS on the network level which lacks attention and is a main challenge in the industrial implementation [18-20], although with a specific focus on the value-chain involved with the system throughout its life-time.

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In order to mitigate the deficiencies, the research question of this paper is: *How can the modular function deployment be modified to support the design of reconfigurable architectures of brownfield manufacturing constituents with consideration of requirements and constraints throughout the value chain*?

The remainder of this paper is structured as follows: Section 2 presents the proposed method, which is applied to a case in Section 3. Section 4 and 5 provide discussions and conclusions.

2. Modified MFD

The proposed method is illustrated in Fig. 1. It consists of phased activities with supportive means that are classified according to the degree of modification relative to the original MFD proposed by *Ericsson and Erixon* [13] where: (blue) indicate a novel addition, (orange) a novel modification, and (red) an addition from extant literature on MFD [10-12, 14-17].

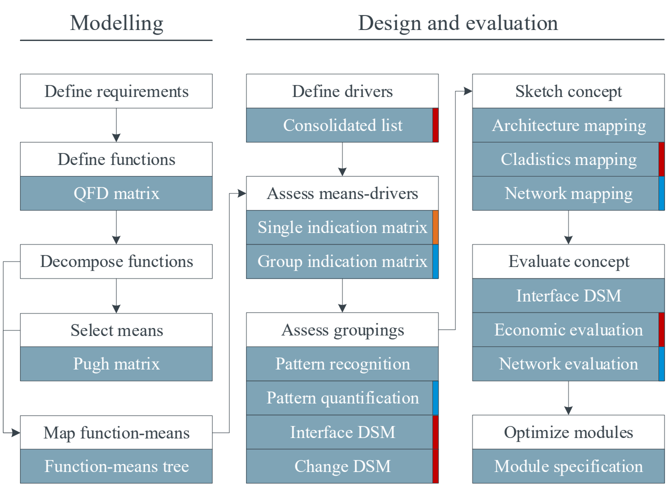

Fig. 1. Activities, sequence, and supportive means in the proposed method.

The definition of customer requirements and translation to functions through the *Quality Function Deployment* is omitted. This is due to the research objective which concerns brownfield manufacturing (mfg.) systems where the required functions can be derived from new and existing counterparts in the product domain and patterns across legacy mfg. systems. Usage of the *Pugh Matrix* for the selection of means is also omitted as it is presumed that similar means, to the ones already applied in brownfield systems, will be applied to new systems. Except, if radical changes are considered i.e., to enable reconfigurability, which would make it more suitable to design several concepts, and thereafter do a more detailed techno-economic evaluation.

The decomposition of functions and selection of means is carried out through a *function-means tree* as prescribed by literature [10-17], although with emphasis on considering the embodiment of reconfigurability i.e., functions and enabling means, from the outset. However, the insights needed to do this might first be generated later when assessing means against drivers. For example, a mean can contain a common part and a varying part which requires further decomposition to enable reuse of the former and differentiation of the latter. This would lead to reiteration, why the sequence should be regarded as an initial guideline where backtracking is possible from every activity. An iterative MFD process is also proposed by [13].

The research of this paper aligns itself with the definition of drivers proposed by [17] as the research objective concerns RMS where the drivers are context-specific and influence the suitable enablers and extent to embody in the system [2, 18, 20-22]. The activity concerns the translation of generic to, and identification of, context-specific drivers [17]. To support the activity, a novel consolidated list of generic drivers from the product and mfg. domains are listed in Table 1 with their respective sources in their related value-chain category. The reason for the consolidation is due the following:

- There is commonality between drivers across domains as both products and mfg. constituents are systems.
- The mfg. drivers do not consider all value chain drivers, specifically between, and after, design and procurement, disregarding that mfg. systems, like products, needs e.g., mfg., storage, transport, and parallel development.
- The product drivers disregard mfg. specific drivers e.g., changeability and life time, which arise due the added complexity of mfg. being interrelated with products.
- The drivers lack consideration of reconfigurability-specific drivers (e.g., reusability), brownfield-specific drivers (e.g., utilization), and scale-specific drivers (e.g., infrastructure).

Table 1. Consolidated list of module drivers from actors in the value-chain.

Category	Driver	Mfg.	Product
Design: change	Carryover	[14-17]	[10-13]
	Planned change	[14-17]	[10-13]
	Technology change	[14-17]	[10-13]
	Regulation change	[15, 17]	[10]
Design: variety	Commonality	[14-17]	[10-13]
	Variety / customization	[14-17]	[10-13]
	Changeability	[15, 17]	
Design: technical	Function sharing	[14-17]	
	Geometric integration	[14-17]	
	Interface portability	[14-17]	
Sales	Parallel activities		[10]
Procurement	Strategic supply	[14-17]	[10-13]
Manufacturing	Process	[17]	[10-13]
	Handling		[11]
	Automation		[11]
Quality	Separate testing	[15, 17]	[10-13]
Inventory	Storage		[11]
Transport	Transportation		[12]
Manufacturing	Infrastructure	[23]	
Maintenance	Maintenance	[14, 15, 17]	[10-13]
End-of-life	Life-time	[15]	
	Utilization	[21]	
	Upgrade	[17]	[10-13]
	Reuse		[10]
	Recycle	[15, 17]	[10-13]

The assessment of means against drivers, is carried out in a *Module Indication Matrix* (MIM) as proposed by [13] with two novel modifications. The first concerns, the possibility to score means for decomposition i.e., a split into multiple modules. This modification is made (i) to enable reuse and differentiation of common and varying means respectively and (ii) as it can be a practical constraint in certain industries that can arise from actors throughout the value chain. This constraint is especially present in the capital goods industry where the extraordinary requirements for space and weight are met by decomposing constituents further than what is functionally needed [23]. Module and split scores are assessed with 1, 3, or 9 points, where split scores are marked with a *. The next modification, concerns a second MIM where means with common scores are consolidated into groups for each driver. The objective of this is to pin-point, and later quantify, groups with similar patterns, as these are subject for potential integration [13].

The assessment of groupings is conducted throughout three supportive activities. The first is through pattern recognition in the MIM as proposed by [13]. The second is a calculation of the total scores for each group followed by a delimitation to groups with scores >9. This is done to quantify and pinpoint, groups of means with highest collective drive for integration. The third activity, concerns the creation of two *DSMs*: one for interfaces between means, and another for commonality degree between means. The latter is considered by literature [10-17] to constrain the selection of modules which contains common and varying means, although a DSM or similar is not proposed as the tool. The former is proposed by [13] although it is positioned after design as it is created for a greenfield context. However, in a brownfield context, it is suitable to account for current integrability constraints during the conceptual design.

Concept sketching can be done in numerous ways, where literature [10-17] proposes to map modules as blocks with in-between lines as interfaces, where a color or duplication scheme is applied to illustrate variety in modules. To support brownfield contexts, *Cladistics Analysis* is proposed [9] where each module is ranked in a hierarchy, or pathway, based on the degree of relative commonality and variety. Moreover, a mapping of module coupling points across the value chain is proposed to ensure that the module strategy is congruent i.e., the formed modules match the capabilities and requirements throughout the value chain [24], for the initial configuration and for any subsequent reconfigurations.

Economic evaluation of concepts is proposed, but the proposal of which evaluation means to apply is left open as it is context-specific in terms of parameters, variables, timeframe etc. An overview of methods and models for evaluation of RMS is provided by [25] where a model with consideration of the value-chain is provided by [26]. The measures provided by [13], are applicable, but not exhaustive as they do not consider the benefits of RMS. For the optimization of modules, they are proposed to be specified as suggested by [13] and assessed from a value-chain perspective in terms of constraints, requirements, and feasibility of the chosen modules. To support the evaluation, a supportive tool is proposed which concerns to map the flow of modules and their (de-)coupling points throughout the value chain across (re-)configurations.

3. Case application

To validate the modified method and its supportive means, it is applied to an industrial case where the company is in progress of re-designing a brownfield manufacturing system to embody reconfigurability by means of modularization.

The case company is a global manufacturer of large-scale capital goods where operations are split into multiple segments, one for each major product module. The case is delimited to the bottleneck segment with the highest volume, variety, and size of constituents which creates a high frequency of resource-and time-intensive changeovers. The segment operates with a wide mfg. footprint and a multi-tiered degree of vertical integration in the development and mfg. of products and mfg. equipment. Within the segment, the case is delimited to the largest and costliest equipment which is the bottleneck with respect to both cycle- and changeover-time across new and existing parts. From a research perspective, a constituent from the equipment level is of interest as there is a lack of research on it [3, 6].

Data i.e., functions, means, drivers, assessments etc. was collected through semi-structured interviews with multiple actors throughout the value-chain e.g., suppliers, transport, system designers, managers etc. at multiple points in time.

3.1. Functional modelling

The defined functions, selected means, and interrelations are mapped in the function-means tree which is presented in Fig 2.

Fig. 2. Function-means tree (in case).

3.2. Design and evaluation

Module and split candidates were identified by assessment of means against drivers in the indication matrix presented in Table 2. Means were assessed with a weight of 1, 3, or 9 where a * marking distinguishes split from module scores. The total weighted module and split scores indicate single candidates.

Table 2. Module Indication Matrix: single means assessment (in case).

	A	B	C	D	E	F	G	H	I	J
Carryover						3^*	3^*	3^*	9^*	3^*
Planned change	9	9	9	9	9					
Technology change								1	3	
Regulation change						3			3	
Commonality	9		9		3^*	9^*	9^*	9^*	9^*	9^*
Variety		9		9	3					
Changeability					3^*	9^*	9^*	9^*	9^*	9^*
Function sharing					3	3	1	1		
Geometric integration	9	9	9	9	9	3	3	3	3	3
Interface portability						3			3	3
Parallel development	9^*	9^*	9^*	9^*	1^*	1^*			3^*	3^*
Strategic supply	9	9	9	9	3	3	3	1^*	9^*	3
Process	9	9	9	9	3	3	3			3
Handling	9^*	9^*	9^*	9^*	3^*	3^*	3^*			3^*
Automation					1^*	1^*	3^*	3^*	3^*	
Separate testing								3^*	9^*	
Storage	1	1	1	1					3	
Transportation	3^*	9^s	3^*	9^s	9^*	9^*	9^*	1^*	9^*	9^*
Infrastructure						3			9	3
Maintenance	3	3	3	3					9	1
Life-time	9		9		3	3	3			3
Utilization					3^*	3^*	3^*			3^*
Durability								1^*	9^*	3^*
Upgrade		9		9	3^*	9^*	9^*	9^*	9^*	9^*
Reuse	9		9		3^*	9^*	9^*	9^*	9^*	9^*
Recycle / dispose	1	1	1	1	3	3	3			3
Module weight	7	7	7	7	4	3	2	1	3	2
Split weight	2	2	2	2	3	6	6	6	8	6
Module candidate	x	x	x	x	x					
Split candidate					x	x	x	x	x	x

A recognition of patterns in Table 2, indicates that A, B, C, and D are strong module candidates, where there is similarity between A and C; and, B and D. In contrast, F, G, H, I, and J are strong split candidates, where there is similarity between F, G, H, and J. In both cases, the similarity indicates integration potentials. Both I and E have unique patterns, which indicates that it is suitable to retain them individually. A somewhat conflicting pattern can be seen for E, as it is a varying means, although, with potential for a degree of commonality if split.

Group candidates were identified by grouping the means with common weight for every driver, which is presented in Table 3 along with a translation of generic to specific drivers. The candidates were then analyzed by quantification of the total weighted scores across drivers, and thereafter delimitated to candidates with total scores >=9, which is provided in Table 4. These groups were then analyzed through DSM in terms of (i) interfaces across means for integrability constraints and (ii) variety-commonality similarity across means for change constraints. These are provided in Table 5, noted with an i or c.

Table 3. Module Indication Matrix: grouped means assessment (in case).

	High	Med	Low
Can carryover across families if split.	I	FGHJ	
Needs to be customized for families.	ABCDE		
Subject for external technology change.		I	H
Subject for external regulation change.		IF	
Can be common within families.	AC		
Can be common within families if split.	FGHIJ	E	
Needs to be customized for variants.	BD	E	
Can be changed by extension if split.	FGHIJ	E	
Can be enabled by shared sub-functions.		EF	GH
Needs to be integrated with precision.	ABCDE	FGHIJ	
Needs to transmit interaction at distance.		FIJ	
Needs to be split to enable parallel development to reduce time to market.	ABCD	IJ	EF
Needs to be sourced at strategic supplier.	ABCD	EFGJ	
Needs to be split to enable multi-source from strategic vendors to ensure supply.	I		H
Subject to similar production processes.	ABCD	EFGJ	
Needs to be split to be enable handling.	ABCD	EFGJ	
Can be automated if split.	GHI	EF	
Needs to be split to enable separate test.	I	H	
Needs to be stored by similar conditions.		I	ABCD
Needs to be split to enable transport.	EFGIJ	AC	
Can be transported with support means.	BD		
Needs to be exchangeable to meet NPIs spatial needs within factories' limit.	I	JE	
Needs to be maintained at same rate.	I	ABCD	J
Subject for similar technical life-times.	AC	EFGJ	
Needs to be split to increase utilization.		EFGJ	
Needs to be split to reduce failure risk.	I	J	H
Can be upgraded within family.	BD		
Can be upgraded within family if split.	FGHIJ	E	
Can be reused within family.	AC		
Can be reused within family if split.	FGHIJ	E	
Can be recycled by similar means.		EFGJ	
Can be disposed by similar means.			ABCD

Table 4. Pattern quantification and evaluation of group candidates (in case).

Candidate	Module	Split	Total	Evaluation
ABCD	18		18	Unsuitable due to integrability and change constraints.
AC	27	3	30	A and C as family modules.
BD	27		27	B and D as variant modules.
E	3	12	15	Split and integrate E across family and variant modules.
ABCDE	23	18	41	
EFGJ	12	6	18	Split integrated FGH and J to standardized extension modules.
FGHIJ	3	36	36	
I	24	36	60	Split I to platform modules.

The quantified scores for the delimited groupings formed the collective outset for assessment of candidates, which was supported by insights gained from the supportive analysis.

Table 5. Design Structure Matrix: interfaces and changes (in case).

	A	B	C	D	E	F	G	H	I	J
A	-	i^s	c^f		i^sc^f					
B	i^s	-		c^v	i^sc^v					
C	c^f		-	i^s	i^sc^f					
D		c^v	i^s	-	i^sc^v					
E	i^sc^f	i^sc^v	i^sc^f	i^sc^v	-	i^s				
F					i^s	-	i^sc^e	$i^{se}c^e$		$i^{se}c^e$
G						i^sc^e	-	c^e		c^e
H						$i^{se}c^e$	c^e	-		c^e
I									-	i^{se}
J						$i^{se}c^e$	c^e	c^e	i^{se}	-

The architecture of the modules and interfaces of the system is illustrated in Fig. 3. The colors indicate the relative degree of commonality that can be traced to the cladistics analysis in Fig. 4. Platform modules are common across families. Extension modules are common across families, where the quantity is extended for each variant. Family modules are common within a family. Variant modules are customized for each variant.

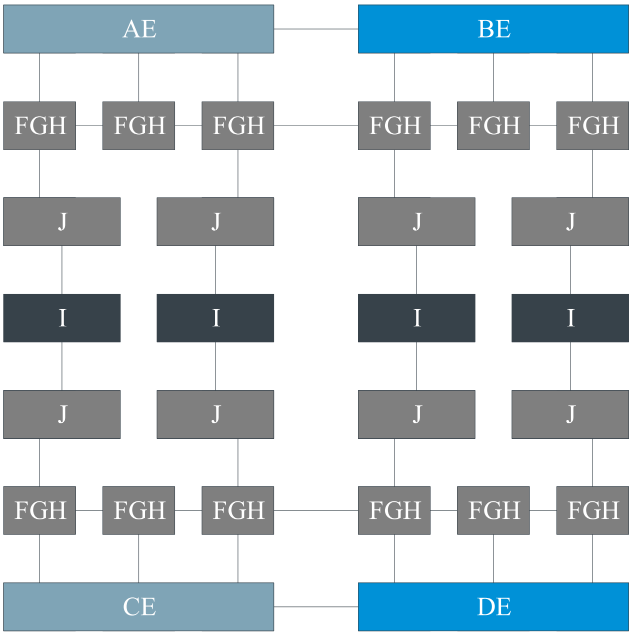

Fig. 3. Modularized architecture (in case).

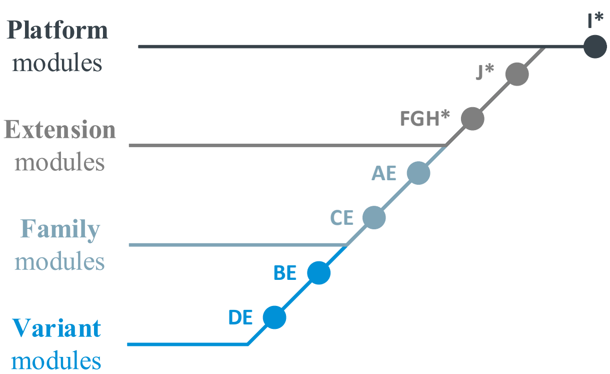

Fig. 4. Cladistic analysis (in case).

It should be noted that the illustrated architecture, solely represents the final assembly once it has been configured, or reconfigured, at the designated factory. To ensure congruency of the architecture throughout the value-chain, the flow of modules and their coupling points are illustrated in Table 6 for the initial configuration, and subsequent reconfigurations. * Markings indicate split modules. + markings indicate assembly of modules from side to main flows. Δ indicate exchange of module from main flows with modules from side flows. Supply denotes tasks at external suppliers, mfg. #1 denotes tasks at the internal supplier, mfg. #2 denotes tasks at the designated factory, where transport occurs in between these tiers.

Table 6. Module couplings in value-chain across configurations (in case).

	Supply	Mfg. #1	Mfg. #1	Mfg. #2
Configuration #1				ABCDEFGHIJ
		A*	AEFGHJ*	+
		B*	BEFGHJ	+
		C*	CEFGHJ*	+
		D*	DEFGHJ	+
	EFGHJ*		+	
	I*			+
Configuration #2				ABCDEFGHIJ
		B*	BE	Δ
		D*	DE	Δ
	E*		+	
	FGH*			+
	J*			+
	I*			+

When assessing value chain requirements and constraints for module couplings against the concept architecture, there are three issues. (i) EFGHJ* is desired for the first configuration due to cost savings from being able to consolidate supply to mfg. #1 and transport to mfg. #2. (ii) F* is needed for reconfigurations as BE and DE cannot be transported without a support structure. The solution to this were a modularized F* which could be disassembled for return to mfg. #1 after reconfiguration. (iii) I* is desired to be dual sourced due to availability constraints, which requires the design of an adapter module which can integrate the interface between I* and J* to avoid variety propagation throughout the remaining system.

4. Discussion

A critical issue of applying the method to industrial cases is the selection of a sufficient level of functional decomposition. In the applied case, it were carried out in multiple iterations where the shaping function required further decomposition, to common and varying parts, in order to enable reconfigurability. As iterations are proposed by [13] the possibility to score for splits were added which support (i) the mentioned iterative decomposition which aids to mitigate constraints imposed by the initial functional model (ii) non-functional modularization which aids to mitigate e.g. logistical constraints preemptively. The former have general applicability and the latter is specific to heavy industries with large tools e.g. the aerospace industry applying large casts to mfg. the integral wings and fuselage.

5. Conclusion

The contribution of this paper extends and expands on the Modular Function Deployment method to support the design of reconfigurable architectures of brownfield manufacturing systems, and constituents, with consideration of requirements and constraints imposed by actors throughout the value chain.

Relative to the extant literature on MFD in Mfg. for RMS, the contribution provides the following: (i) A consolidated list of drivers across the value chain where six are translated from the product domain, and two from the RMS domain, (ii) a modification of the MIM to assess means for splits to enable applicability of the model in the capital goods industry, (iii) an extension to the MIM to quantify and pinpoint groups of means with similar patterns, (iv) a modification of the MFD with supportive tools e.g., change DSM and cladistics analysis from the RMS domain, (v) an approach to map module (de)coupling points throughout the value-chain across configurations to assess the congruency of the chosen system architecture. The latter was done in response to the research gap on the network level and on co-development. In addition, the method was applied in a case at a global manufacturer of capital goods, which aided to validate (i) the modifications proposed in this paper and other papers and (ii) the applicability of MFD in the domain of large-scale discrete manufacturing equipment.

Practical implications would be to enable engineers to design reconfigurable manufacturing systems in brownfield contexts with reduced risks throughout the value chain. Efforts were made to quantify group patterns such that the method has increased applicability for complex systems. Although, only to a certain degree, why future research is proposed to introduce clustering or hierarchical decomposition as MFD extensions.

A prerequisite for design is an object to design, which is not always obvious when searching for manufacturing constituents with potentials for embodiment of a reconfigurable architecture in a brownfield context. Therefore, future research is proposed on the design and application of methods with this objective.

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