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**Abstract.** The capital goods industry supplies highly volatile marketplaces with products customized to increase product performance and reduce operating costs. Consequently, an order winning criteria for capital goods manufacturers is to quickly and effectively reconfigure supply and manufacturing systems to suit ever changing product and volume requirements within short time frames. In order to clarify such potentials of reconfigurability, this paper presents a case study on reconfigurability potentials in a large capital goods company. The framework applied for this relates reconfigurability drivers with different production levels and purposes. The findings suggest that local content and sub-contracting requirements are main drivers for the potential application of reconfigurability on network level, being reinforced by reconfigurability on system and equipment level. Thus, the paper extends previous research on reconfigurability and addresses potentials beyond shop floor level in a multi-dimensional approach.

**Keywords:** Reconfigurable Manufacturing, Configuration, Case Study.

## 1 Introduction

Today's global manufacturing environment is characterized by several trends that challenge traditional manufacturing concepts and entail development of new changeable and reconfigurable concepts which at the same time are efficient and responsive [5]. For instance, in high-value manufacturing, a stage-wise postponement of committing order specifications is often required by the customer due to uncertain requirements, rapidly shifting local regulations, frequent new product offerings, and increased local content requirements [13]. Such conditions are particularly challenging in the capital goods industry, where engineer-to-order (ETO) products are sold through highly competitive tendering schemes and postponement of order specifications has a profound impact on multiple levels of the supply chain and manufacturing system [4]. Thus, capital goods manufacturers must be able to rapidly react and reconfigure supply and manufacturing systems with the aim of producing multiple customized product variants. Moreover, such companies must be scalable in terms of adjusting capacities for different variants, for new products, and for changing order sizes [12].

Thus, in capital goods manufacturing, the scope and rapidness of changes that need to be handled cost-efficiently is generally increasing. For this purpose, product modularization and configuration has been widely addressed, providing various methods and tools for creating configuration models, making these models available to the market through a configuration system, and establishing configuration tasks to specify the final product configuration [11]. However, improved responsiveness and efficiency for manufacturing and suppling increasing product variety and customizations, made available through the configuration system, is likewise needed. In regard to this, the Reconfigurable Manufacturing System (RMS) was introduced in the 1990's along with the concept of reconfigurability being an engineering technology providing less costly and quicker response to unpredictable market changes [9]. Reconfigurability is a system´s ability to change its structure and resources rapidly and cost-efficiently, in order to possess exactly the capacity and functionality needed, exactly when needed [8]. To achieve reconfigurability, a system must have the following enablers; modularity, integrability, customization, scalability, convertibility, automatability, mobility and diagnosability [2]. To harvest the benefits of reconfigurability, it is crucial to realize these enablers on multiple productions levels spanning from equipment and workstations at individual manufacturing sites, to complete factories and global supply networks [7]. This is particularly evident in the capital good industry, where supplying products requires a complex interrelated network of assembly and production. However, previous research on reconfigurability has mostly focused on its potentials and applications on shop floor level in settings with medium to high manufacturing volume and with limited consideration of the complete manufacturing network as well coverage of manufacturing settings relying on ETO principles [1], [3]. Thus, the objective of this paper is to establish an overview of potentials for reconfigurability on multiple production levels and their relationship towards reconfigurability drivers and purposes, using a case study from the capital goods industry as the empirical foundation.

The remainder of the paper is structured as follows: Section 2 present the research methodology, while Section 3 presents the findings from the case study in accordance with the applied framework for reconfigurability potential assessment. Section 4 conclusively summarizes the results and provides future research directions.

## 2 Research Methodology

In order to investigate potentials for reconfigurability across multiple production levels, the research presented in this paper applies an explorative case study in a company manufacturing capital goods for the energy sector. The company has a yearly revenue of 10,1 bnEUR, has 24.648 employees and is a market leader with a global reach of 43 countries and a manufacturing footprint of 73 factories in 24 countries. The case study research method can be described as the study of past or current phenomenon drawn from multiple sources of evidence, for example interviews, observations and archives

[10] and is well suited when the researched phenomenon needs to understood in its context, and where exploration of concepts and variables may be needed [14]. Thus, the case study presented here consists of semi-structured interviews with 12 central employees covering 8 meetings with approximately 60 minutes duration. The interviewees include vice presidents, production engineering specialists, factory managers and global industrial senior specialists in modularization and supply chain management. Two of the interviews were further combined with factory visits and half day workshops. Each interview began with a background introduction to the concept of reconfigurability, followed by 3 primary questions; 1) Which, if any, reconfigurability initiatives exists in the company? 2) What are the potentials for reconfigurability in the company? 3) Who are the stakeholders for reconfigurability in the company? Extensive field notes were taken during the interviews and factory visits, which were afterwards coded and categorized in “drivers” and “potentials”. Each driver was further grouped based on impact similarities. The potentials were categorized based on whether they would benefit change in manufacturing of different variants, change in manufacturing of different volumes or change due to the introduction of new products. As the last step, the drivers and the grouped potentials were assessed and consolidated to one or more production levels. This relational overview was finally shared with the involved stakeholders for the sake of validation and to receive feedback and make final adjustments.

# 3 Case Study Findings: Potentials of Reconfigurability

## 3.1 Manufacturing Reconfigurability Drivers

In the case study, 27 drivers of reconfigurability were discovered and consolidated into 5 main categories, see Fig 1.

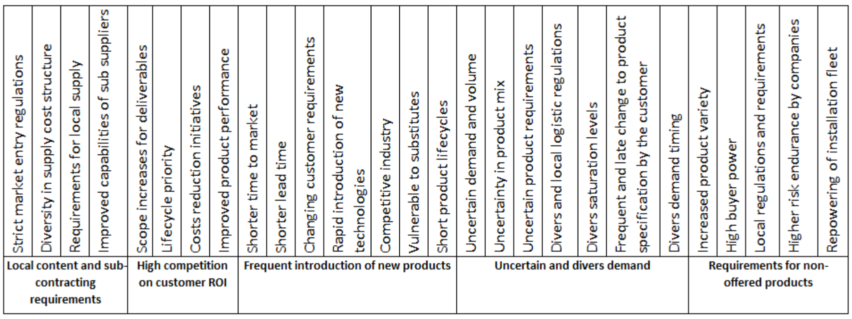


**Fig. 1.** Reconfigurability drivers and their categorization.

The company operates in an environment where strict regulations for entering local markets exist and local suppliers are emerging and improving capabilities to match or exceed the quality of the dominating manufactures. Therefore, a continuous need to reduce lifecycle costs and manufacturing costs exists, in order to improve return on investment (ROI) for the customer without compromising product performance. Furthermore, the company encounters high needs for frequently adapting the supply system to new product introductions and rapidly shifting and uncertain product specifications, amplified by shorter time to market, shorter lead time, vulnerability towards substitutes and local divers logistic and installations requirements. Lastly, an important driver is the supply system´s ability to support the sales and production of products not yet designed, ETO products, as well as reinstating phased out products in manufacturing to repower existing products or create new deliveries in sales projects.

### 3.2 Production Levels and Reconfigurability Objectives

In order to classify and analyze potentials of reconfigurability triggered by the drivers, a hierarchy of production levels is adopted from ElMaraghy and Wiendahl [6]. The relationship between each production level and the product structure is depicted for the case company in Fig. 2.

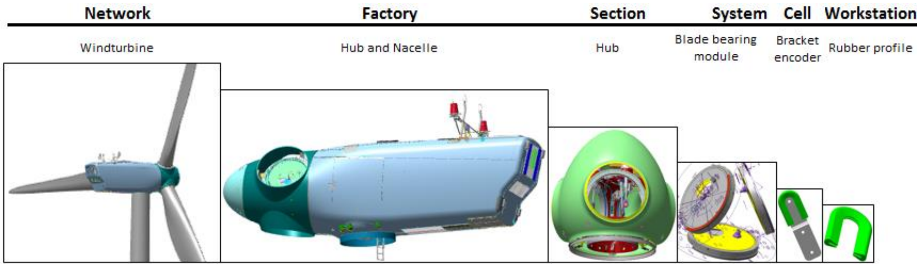


**Fig. 2.** Relationship between production levels and product structure.

The lowest level contains the workstations. Workstations apply one or multiple manufacturing techniques on a workpiece to transform it into a part element. The next level is a grouping of manufacturing resources into cells, consisting of multiple workstations that transforms multiple part elements into a single assembly part. On the system level, different variants of product modules/building blocks are manufactured from a collection of cells. The bracket from the cell level in Fig. 2 is part of the blade bearing module´s BoM at the system level. Combining different product modules at the section level creates complete products ready to be shipped. In the case company, factories produce multiple products, which are either assembled and shipped or shipped separately and assembled at the construction site. The last level is the network level, which consists of interconnected factories producing different products. At the network level, products from multiple factories e.g. blades, tower and controls are shipped to the construction site and assembled to form the complete wind turbine. The drivers for reconfigurability impose changes to the supply system on all production levels. The potentials for accommodating these changes through reconfigurability depends on the purpose of the change, the reconfigurability driver and the production level. This research therefore applies the reconfigurability objectives suggested by Tracht and Hogreve [12] to further focus reconfigurability potentials and their objectives. The objectives are: 1) Variant: Reconfigure the supply system from currently suppling one kind of variant to suppling different ones, 2) Capacity: Reconfigure the capacity of the supply system to either increase or decrease supply volume, and 3) Product: Reconfigure the supply system to adapt the supply of new products.

### 3.3 Potentials of Reconfigurability Considering Multiple Levels and Objectives

The potentials for implementing reconfigurability identified in the case company are mapped with drivers, objectives and the six production levels described in the previous subsections, see Table 1. On the left-hand side, the 3 objectives for reconfigurability (V=variant, C=capacity, P=product) are represented for each of the 5 drivers. The combinations of drivers and objectives are mapped with reconfigurability potentials for each production level, represented at the top. The table should be explored by reading the potentials in combination with its drivers and objectives at different production levels. For example; the increase of local content requirements drives the company to reconfigure the supply system at the network level so that local supply chains are enabled to supply localized markets with multiple product variants from local suppliers.

**Table 1.** Empirical findings of potentials for reconfigurability.

| | | Network | Factory | Section | System | Cell | Workstation |
|---|---|---|---|---|---|---|---|
| Local content and sub-contracting requirements | V | - Supplying localized markets with multiple variants from local suppliers | - Reusing technology and operational approaches across multiple products | - Increase mobility through the factory in a box concept | - Enable division of work for specialized local suppliers | | |
| | C | - Enabling suppliers to produce near the customer<br>- Rapidly establish and expand local capacity<br>- Scale and adapt distribution of product variants<br>- Share capacity between manufacturing hubs thereby chasing local demands and reducing inventory | | - Decrease capacity loss though linking diagnostic capabilities with sub suppliers and manufacturing systems by means of harvesting local manufacturing data through a common manufacturing platform | | | |
| | P | - Entering new markets faster by establishing local configurable supply chains | - Confine impacts of manufacturing implementation of local product variants | - Adapt to different local cost structures | | - Faster implementation and ramp-up of local suppliers<br>- Sharing manufacturing setup with other industries thereby increasing the use of qualified suppliers | - Improve utilization of local capabilities due to standardization of manufacturing techniques<br>- Adapt manufacturing equipment to local regulations |
| High competition on customer ROI | V | - Reduce costs by establishing industry standards across competitors thereby enabling sub-suppliers to benefit from producing similar components | | - Increase mobility through the factory in a box concept | - Enabling the division of highly process oriented manufacturing into a more cost-efficient assembly sequence | | |
| | C | - Improve portfolio profits by adapting capacity to the most cost-efficient supply for each sale project | - Reduce transport cost by producing smaller assemblies which fit within a standard container | | | - Establish automatability to reach optimal balance between manual vs. automated manufacturing processes<br>- Automating standard parts of operations<br>- Faster training of personnel due to division of labor<br>- Standardized manufacturing resource interfaces | |
| | P | - Reduce costs by establishing supply chain interface management and reuse relevant parts of existing setup | - Faster maturity of margins due to faster and less expensive ramp-up | - Enable optimization of production setup without compromising future product design and performance | - Designing for economies-of-scale for relevant parts of the product | | |
| Frequent introduction of new products | V | | - Manufacturing resources can be configured to manage product families with different weight and space requirements | | | | |
| | C | - Portfolio approach to incremental implementation of new products in production | - Configurable and scalable buildings/facilities for space and weight adaptation | | | | |
| | P | - Reduce time to market by reusing distribution setups between factories and customers by having a global lead factory concept | - Faster integration of new products in brown-field manufacturing<br>- Reduction of cost for certification and testing | - Reuse of testing equipment functionalities and rapid prototyping<br>- Reuse of manufacturing resources<br>- Control and alignment of change in product modules with the manufacturing setup | | - Faster and more flexible rearrangement of workstations<br>- Reduction in time for changing the manufacturing layout for new products | - Reuse and smaller adjustments to equipment architectures for lifecycle cost reductions<br>- Increase equipment lifetime by modularizing the replenishment of spare parts |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Demand uncertainty and diversity | V | - Increase supply responsiveness independently of product mix | - Reduce transportation costs when implementing large manufacturing equipment shipped from lead factory | - Better exploitation of space in manufacturing and storage areas | - Responsive production planning due to standardization<br>- Modular relationship between product properties and manufacturing functionalities | - Information configuration e.g. documents, routings, work instructions etc. | - Faster change-over between operations |
| | C | - Faster scaling of supply network capacities and capacity on demand | - Scaling of capacity according to demand thereby reducing product inventory and increasing profit | | - Easier line balancing when shifting between variants and rearrangement of workstations to even-out takt-time for bottlenecks | | |
| | P | | | - Adaption to new and old technology introductions in manufacturing | | | |
| Requirements for non-offered products | V | - Reuse of manufactured ETO parts across multiple product variant | | | - Parameterized manufacturing to optimize product performance for specific customer sites | - Integrate additive manufacturing with reconfigurable manufacturing thereby increasing ETO manufacturing capabilities | |
| | C | | | - Reduce capacity consumption of ETO products | - Enabling production of phased out product variants | | - Adaptable flexibility to cope with ETO design while maintaining the benefits of mass production for standard products |
| | P | - Long term manufacturing design based on product roadmap<br>- Faster alignment between ETO and standard manufacturing across products | | - Minimize information needed to prepare and design manufacturing setups and equipment | | | |

It should be noted, that the results in Table 1 solely present initial explorations of reconfigurability potentials gathered during the interviews and thus do not address how these can be realized or achieved in detail through specific reconfigurable solutions. In the following, the potentials are described in detail.

**Local content and sub-contracting requirements**

On the network, factory and system level, the reconfigurability potentials are focused on the mobility of manufacturing resources and the fast establishment of local supply chains, with the purpose of producing closer to the customer and reduce inventory by moving capacity among manufacturing hubs and suppliers. A further focus is the potential of diversifying the design of manufacturing setups depending of local cost structures. For example, in some countries it is more profitable to employ manual labor instead of automated machines. On the system, cell and workstation level, the potentials are dedicated to an easier division of work between local suppliers and standardization of manufacturing techniques across industries to increase the use and scope of local suppliers and reduce ramp-up time for local supply.

**High competition on customer ROI**

The company has initiated a network and factory level initiative across competitors to standardize both product and manufacturing design, thereby reducing cost for suppliers producing sub-components. The mobility and integrability enabled by reconfigurability will further empower the company to produce a more diverse range of variants at each factory, thereby reducing the cost for the entire portfolio of sales projects and a more rapid maturity of margins due to planning production where it is most cost-efficient compare to the demand. At the section and system level, the main potential is to divide the process-heavy manufacturing steps into more cost-efficient assembly operations and further ensure economies-of-scale benefits for standardized components without compromising product design and performance.

**Frequent introduction of new products**
When introducing new products into the supply system, the emphasis is given on practical issues for capital goods, namely their extraordinary requirements for space and weight. These requirements apply from the network to the system level, as the components at these levels are large enough to cause challenges. These challenges can be diminished by designing modularized, scalable, configurable buildings, equipment, distribution tools and testing facilities on an incremental factory by factory basis.

**Demand uncertainty and diversity**
When changing between products in manufacturing, the potentials are mainly related to the enabling of the supply network to deliver capacity on demand and thereby become responsive independent of which products are sold. On the factory and section level, the focus is again on the size and weight requirements of the products. At these levels, cost reduction is sought by modularizing large transport and manufacturing equipment, which further enables a more optimized exploration of space when changing from one variant to another or moving the product between manufacturing cells. On the cell level, the great potentials of reconfigurability is within information configuration and planning. The mobility of resources in the manufacturing system enables the rearrangement of workstations and easier line balancing when changing between variants.

**Requirements for non-offered products**
Non-offered products can be both previously produced products, ETO products and products still in the development phase. Reconfigurability is challenged by this driver because of its dedication to the offered product program. The most significant potentials are adaptive flexibility on cell and work station level by the means of integrating additive manufacturing techniques (e.g. 3D printing) together with reconfigurability to keep mass efficiency for standard products, but with the ability to add additive resources with the purpose of further customization. On the network and factory level, the company can benefit from reconfigurability by aligning manufacturing and product development roadmaps, thereby preparing long term ETO product demand together with increased efficiency.

## 4 Conclusion and Future Research

The objective of this paper was to establish an overview of potentials for reconfigurability on multiple production levels and their relationship towards reconfigurability drivers and purposes, using a case study from the capital goods industry as empirical foundation. The multi-level approach enables a contribution to the body of literature by presenting a consolidated assessment of potentials for the entire supply system, which appears particularly suited in large enterprises and capital goods companies. The case study shows that reconfigurability should be regarded on all production levels to fully realize the potentials within each driver for manufacturing changes. The potentials are mostly triggered by the drivers for *local content and sub-contracting* requirements, as well as *customer ROI* and *demand uncertainties and diversity*. Both potentials and drivers are consistent with current knowledge but are now further empirically investigated and structured across all production levels and additionally related to manufacturing change objectives. The structural relationships are represented in a matrix format and categorized for its implication of applying reconfigurability. The drivers are argued to be general applicable across the capital good industry, whereas the potentials are case specific for companies supplying large products through global supply networks, and where ROI for the customer is the main order winner.

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