Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 50 (2016) 589 – 594

www.elsevier.com/locate/procedia

26th CIRP Design Conference

Co-Definition of Product Structure and Production Network for Frugal Innovation Perspectives: Towards a Modular-based Approach

Farouk Belkadi[a,]*, Jens Buergin[b], Ravi Kumar Gupta[a], Yicha Zhang[a], Alain Bernard[a], Gisela Lanza[b], Marcello Colledani[c], Marcello Urgo[c]

[a] *Lunam université IRCCyN – Ecole Centrale de Nantes, UMR CNRS 6597, 1 rue de la Noë, Nantes, France*
[b] *wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), Kaiserstrasse 12, 76131 Karlsruhe, Germany*
[c] *Department of Mechanical Engineering, Politecnico di Milano, via La Masa 1, 20156 Milano, Italy*

* Corresponding author. Tel.: +33-240-396-954; fax: +33-240-396-930. *E-mail address:* firstname.lastname@irccyn.ec-nantes.fr

Abstract

Frugal innovation theory is proposed to help companies rethinking their current product design and production strategies facing competitive challenges. Co-evolution of product and production systems is required to reach frugality goals. The success of the co-evolution strategy should be based on robust models ensuring the global consistency of the whole development process. Modular-based models are a good solution for such problematics since they provide a common semantic for the representation of the physical product structure as well as the organizational structure of the production system through the definition of interfaces between elements and the hierarchical decomposition of a system into different elements.
This paper proposes a conceptual modular-based approach dealing with the selection of product modules influencing the selection of suppliers and the allocation of orders in a global production network. The indirect linking of the customer to production is also discussed in terms of the timewise restrictions in selecting product modules offering the customer a maximum degree of flexibility in product specification.

Keywords: Frugal innovation, modular approach, co-evolution

1. Introduction

In the new vision of the industry of the future, companies should adopt new flexible strategies to deal with the huge varieties of competitive markets and complex needs of customers, correlated by specific cultural, social, political and economic specificities. This implies the development of new products and services for several markets (i.e. emerging markets) with acceptable quality and optimal cost regarding the socio-economic context of the targeted market.

Indeed, the high growth rates, huge market size and workforce in emerging countries have ensured sufficient focus on "winning in emerging markets" through region appropriate strategies [1]. Hence, the traditional products and services with complex features and functions sold in western markets should be modified to obtain attractiveness according to frugal criteria [2]. Some products or services even should be developed from scratch by involving regional R&D in local regions to capture the regional market needs and features [3].

In this new challenged context, frugal innovation theory seems to be an efficient solution to cope with these issues by providing experts a set of technical and managerial tools helping them with the identification of the exact customer needs in specific markets but also rethinking their current development processes to answer these needs with affordable cost and best quality.

Thus, creating new frugal products or services for regional markets can be obtained through the definition of new product features or the adaptation of existing products regarding the constraints of the targeted context.

doi:10.1016/j.procir.2016.04.160

However, the (re-)design of the product structure is not already sufficient to reach the frugality goals. Additionally, the (re-)definition of the production network structure and processes based on heterogeneous capabilities can contribute to the optimization of the final solution in terms of cost, quality and time to market.

This paper discusses the potential of using a modular-based approach as a kernel methodology to reach the frugal innovation objectives by supporting the co-evolution of product structure and production strategy. The application of such an approach is discussed through some inputs from real use cases about how the selection of product modules influences the selection of suppliers in a global production network and the allocation of orders in such a network.

The next section focusses on the main characteristics of the frugal innovation theory and the co-evolution strategy as main pillar of this theory. The third section describes the foundations of modular approach method and its advantages to support frugality. The last section presents the utility of the proposed approach from a practical point of view.

2. Co-evolution for frugality perspectives

Frugal innovation theory is introduced to explain new market trends and to propose new solutions supporting these evolutions [3]. For Tiwari and Herstatt [4], frugal innovation refers to innovative products and services that “seek to minimize the use of material and financial resources in the complete value chain (from development to disposal) with the objective of reducing the cost of ownership while fulfilling or even exceeding certain pre-defined criteria of acceptable quality standards”.

In general, five main directions for frugal innovation are identified as efficient levers to develop frugal products for specific markets with optimal costs and quality:

- Develop new products from scratch in local R&D centers.
- Develop frugal products as an adaptation of existing solution for local markets, by:
  - ✓ Replacing current materials with cheaper but functional ones;
  - ✓ Removing non-essential product and service features from current products and services;
- Re-design the production network by increasing the proportion of regional suppliers;
- Modify current production processes and strategies to reduce manufacturing and logistic costs.

According to these directions, the co-evolution of product, processes and production systems and the consideration of their reciprocal influences with the strategic decisions of the company are often required to reach economic and social sustainability in the frugal context. Herein, the change propagation behaves as a cause–effect wave across the enterprise, spanning all product, process and production system dimensions. According to Tolio et al., [5] the term ‘‘co-evolution’’ represents the ability to strategically and operationally manage the propagation of engineering changes to gain competitive advantage from the resulting market and regulatory dynamics.

The co-evolution of the production system is usually extended to the production network level that aims to create several collaborative relations between OEM and supplier companies for a better management of their distinctive skills and resources in the whole production process. Supplier selection and evaluation are among the main factors to be resolved at the earlier stage to guarantee successful results from any OEM-Supplier collaboration [6].

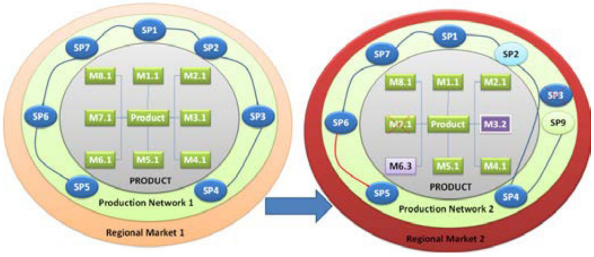

Fig. 1. Frugal Innovation: adaptation of existing product to new market

The co-evolution of product structure and production systems to adapt an existing product to a new market can be summarized in figure 1 as follows: some of the current product features are modified in order to fit the regional customers’ needs. These features surely belong to some modules (Mx.y), composing the architecture of the product. Accordingly, the production network consisting of a set of production systems, i.e. plants, and/or suppliers (SP) may be changed to support the new modification. Even, deeply, the product’s production with its realization systems and technologies are also affected. Additionally, the design may also be modified when there is a need to redesign some features or develop new product modules of the current product for the adaptation. Therefore, to realize frugal innovation along this direction, a couple of key problems should be dealt with, such as:

- How to identify the right product modules, features or functions to be removed, modified or even renewed?
- How to integrate the customers into the modification and/or development process?
- How to adapt the current production to the modified product features for the new regional markets?
- How to re-design the supplier network for this adaptation?
- How to reuse the knowledge of regional product development in the future?

The success of any co-evolution strategy should be based on robust models ensuring the global consistency between all development stages (from product design to production network configuration) and supporting the propagation of decisions through all managerial levels. The power of modularity for such problematics is clearly laid out in the literature [7] since it consists of decomposing complex systems into independent but interconnected parts that can be treated as conceptual, logical or physical units as well as organizational units [8].

The next section discusses the main advantages of the concept of modularity to address the above questions for the implementation of the frugal innovation approach.

3. Modular-based approach as support for frugal innovation principles

3.1. Modularity concept for frugality objective

Product architecture is the way by which the product functions are arranged into physical units and the way in which these units interact to implement these functions [9]. This concept is strongly connected to the concept of a module, which represents a physical or conceptual grouping of product components to form a consistent unit that can be easily identified and replaced. Modularity is the concept of decomposing a system into independent parts (modules) that can be treated as logical units [10].

Based on the modularity concept, Hubka and Eder [11] define the modular design process as "connecting the constructional elements into suitable groups from which many variants of technical systems can be assembled". As an output of this process, a generic product architecture (GPA) can bring cost savings and enable quicker introduction of multiple product variants, through the concepts of product family and configuration mechanism [12]. The whole product structure is obtained by the specification of modules' interfaces to support connections between modules in specific configurations.

The GPA can be constructed by using different methods [13, 14, 15]. However, the fundamental ideas are common: Break systems into discrete modules; ensure modules interchangeability with other ones; and provide well-defined interfaces between modules in the targeted GPA. Thus, modularization consists of deciding about the characteristics used to group and deciding about the characteristics used to separate different components in one common module.

Matching frugal innovation requirements to modularity provide great interest at methodological and operational level for the definition and the deployment of the frugal innovation strategy in different competitive contexts.

Indeed, the main levers for an efficient implementation of a frugal strategy can be summarized by three items: exact understanding of and answering to the customer needs without any sophistication; design new products based on the adaptation of existing solutions; reaching cost optimization through additional levers different from technical product solutions only (i.e. production system improvement and re-organization as a consequence of a new product structure).

As an answer, a modular-based product development approach is proposed with the aim to provide a common semantic for the representation of the physical product as well as organizational structures through the hierarchical decomposition of a system into different elements and the definition of interfaces between these elements. The following applications justify the potentials of the proposed modular-based approach to deal with frugality problems in the adaptation of existing products to specific regional markets:

- **Increasing product variety for regional adaptation.** Different product configurations can be built as an adaptation of existing products or the creation of new ones through the combination and connection of existing modules developed separately in previous projects. This can improve the possibility to propose to the customer different configurations and options to be selected and easily customized with low development cost.
- **Improving the product development for regional market adaptation in a systemic level.** By using the modularity concept, the complexity of the product development process can be reduced through the decomposition and the relative independence among different modules, but also the connection of different product's life cycle stages through the extension of modularity to organizational and operational views. By the matching between product modules, process modules and production capabilities, the development of a product for a new market can be obtained through a concurrent adjustment of the design, the production strategy and the production network as a global solution.
- **Involving the customer into the product development process** through easier clarification of his needs as an intuitive combination of functions and options. These functions can be connected to pre-defined modules. Using the modular-based approach can reduce the complexity of customer interaction by engaging customers only in the modules which they are interested in and presenting a high potential of adaptation. Also, by proposing customization possibilities based on pre-defined modules, the customer can get a rapid but faithful overview about the final structure and performance of the final product.
- **Facilitating knowledge reuse.** By improving customers' interactions, more knowledge about customer needs product performance, improvement direction, etc., can be captured and associated to specific modules. This knowledge can support to project the developed products to other similar markets, having similar customer requirements. The modularity concept can be used to represent the completeness of knowledge as an accumulation of different reusable fragments, available at the beginning of a new development project. The innovative character depends on the completeness level of these knowledge fragments at the beginning of the project.

The main question to be resolved here, concerns the characteristics which the concept of modules should adopt in order to cope with the frugality requirements. The added value of the proposed approach beyond the state of the art is the use of product modules to connect different dimensions of the product development process. Specific features are defined with the module concept to support decision-making processes along the development process of frugal products.

The next section presents the main directions of the proposed modular-based approach derived from product module conception to support frugal innovation in the customer-driven context. The above applications during product development stages are under consideration for airplane customization, domestic appliances regionalization and production plant design use cases in the European project named "ProRegio".

3.2. Modular-based approach for frugality perspective

With respect to the frugal innovation principle, the proposed modular-based approach should handle the easier interpretation of customer requirements and the identification of modules to be considered for the customization process.

In parallel, the approach will handle the definition of all possible solutions for customer requirements as a combination of product modules, the characteristics of these solutions but also all production possibilities for each product modules. Product functions, product modules, module features and solution alternatives are the main aspects that are to be considered to take into account the requirements.

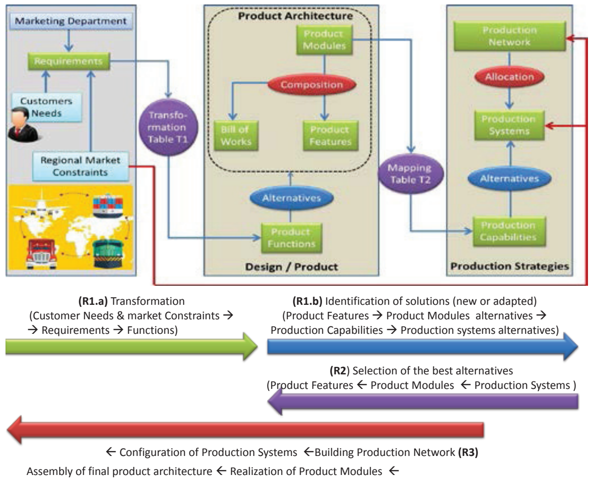

Fig. 2. Proposed modular-based product development approach from customer needs to production network

Figure 2 describes the main concepts of the proposed approach organized among three complementary pillars and three routes ensuring the navigation between these pillars.

- **Requirement pillar:** to collect and classify all customers' needs; regional market properties and frugality constraints for the targeted business context. These requirements collected at this pillar from the earlier stages of the project will be exploited on the following two pillars at three levels: (i) identification of product functions, (ii) selection of a product structure and modules, (iii) identification of the best production systems and network configuration.
- **Product definition pillar:** to identify possible alternatives of product structures and product modules to fulfil all requirements identified in the previous pillar and also to connect product structure and modules to production capabilities and required services in the global network. The identification of product modules is based on the previous stage of transformation (T1) of all identified requirements to a set of functions with respect to the interface constraints in the final product architecture.
- **Production pillar:** to identify production capabilities and then identify best combination of production system against frugal attributes, regional market constraints and company policies. The combination of production systems in this pillar is used to build the global production network [16] based on the list of current suppliers and the company's production capacities but also potential other suppliers from the regional market.

The connection between the three pillars is ensured in the route 1 (R1.a and R1.b) by two tables: the first one (T1) contains the rules to transform requirements collected in pillar 1 to a set of functions with related features representing the conceptual solution. The concept of features is considered as a generic term that includes technical characteristics used for the engineering perspective as well as input for decision-making criteria useful for the deployment of a customer-driven design process in the context of frugal innovation.

The second table (T2) aims to define the mapping between known product module solutions and all related possible production capabilities, which inform about the possible standard manufacturing processes and technologies able to provide the product module with the desired characteristics.

The identification of all possible alternatives of modules responding to the selected list of functions and all alternatives of production capabilities and systems dealing with the realization of these modules are identified in route R1.b, either collectively through the reuse of existing generic product matching with all requested functions, or by mapping functions individually through features and then identifying related product modules. In this last case, more flexibility is allowed for the selection of product modules and consequently more innovative possibilities for the final product alternatives exist. However, more attention is required for the global consistency of the whole structure.

The selection of the best alternatives of solutions is fulfilled in R2 as a decision-making taking in consideration different market requirements, production capabilities and all facilities of the production network. Then the selection of the best module solutions can be obtained as a consequence of selecting the related production systems.

Based on these decisions, the last route (R3) concerns the implementation stage of the selected solution at the three levels (production network, production systems and product modules). By fixing the different production systems (for final assembly and for the production of modules by suppliers), the structure of the production network is defined as a combination of the selected items and the expected behavior of the network is obtained by the definition of the global planning and all collaborative processes supporting information and material exchange between these production systems. Then, the configuration of each production system consists of the definition of local planning and adaptation of working processes to integrate collaboration requirements. In the same manner, by fixing a production system, the related production capabilities and then the bill of work to obtain the related product module are automatically fixed. The assembly process of the whole product structure is obtained according to the global production planning at network level.

4. Potential of the proposed modular-based approach for application in industry

The proposed modular-based approach for frugality has great potential for implementation in industry. The approach has been developed in the European project "ProRegio" applying it to domestic appliances (e.g. refrigerators) as well as aircrafts.

Despite the big differences in the structure of these two products and the productions systems required for realizing them, customers (households in the case of home appliances and airlines in the case of aircrafts) have specific needs regarding these and also other products.

Requirements (for example size and interior of a refrigerator and cabin configuration of an aircraft) may depend on regional markets or market segments i.e. a collective of individuals or even on individual customer. Companies producing such products may only be competitive addressing these customer needs not neglecting differences in requirements regarding one product.

In general, planning tasks for the realization of products can be hierarchically decomposed in strategic (long-term), tactical (mid-term) and operational (short-term) planning tasks depending on their planning horizon [17, 18]. The realization of the modular-based approach for frugal innovation requires the co-definition of product structure and production network on a strategic as well as on a tactical and operational level as the decisions to be made long-term are different from those to be made short-term.

Strategic Decisions regarding the co-definition of product structure and production network are the following:

- **Product development:** The generic product architecture and its modules are developed using existing and newly gained knowledge about customer requirements.
- **Production network design:** The location for final assembly facilities of products have to be determined depending on factors like the location of potential customers as well as locally available resources. Based on product development, it has to be decided which production capacities should be installed at which production location in order to assemble which modules.
- **Supplier selection:** All developed modules that potentially can be assembled according to the generic product architecture have to be sourced from either internal or external suppliers. Therefore, suppliers have to be selected for each module taking into account the distance from each potential supplier's production facility to the each final assembly facility.

Decisions to be made at the tactical and operational level are restricted by the decisions already made on the strategic level, but can provide feedback to the strategic level so that strategic decisions can be adjusted in the long run. The main difference of the two levels besides their time horizon is that, the global modular approach applied on the strategic level is not based on actual customer orders as it is the case for its application on the tactical and operational level. Tactical and operational level decisions regarding the co-definition of product structure and production network are the following:

- **Product configuration:** Customers may configure their product by selecting modules offered to them from the generic product architecture. Enabling frugal innovation not being limited to existing modules, a feedback mechanism should be implemented for collecting customer needs which are not aligned with the offered modules. Alternatively, customers articulate required functions that are translated into modules. Based on specific information about customer requirements, new modules can be developed as part of the strategic product development meaning that new modules need more time to be realized in the first run.
- **Order allocation:** Each customer order, i.e. each product configured by an individual customer, has to be allocated to a final assembly facility for production. Based on production network design, all facilities being capable of assembling all selected modules are valid for an order to be allocated. Moreover, the maximum availability of production capabilities within a certain production period restricts the number of orders with its specific modules to be allocated to a period. Additionally, the distance from a customer's location to the final assembly facility may also be taken into account when allocating an order.
- **Ordering modules:** For each customer order the selected modules have to be ordered from suppliers depending on the allocation of the order. Therefore, limitations regarding the maximum quantity of modules produced by suppliers have to be taken into account for each period. In this context, also the time for transportation to the respective final assembly facility has to be considered.

Regarding the direct interaction with customers in terms of the order fulfilment process, the tactical and operational level is of major interest. In order to order modules from suppliers for final assembly of an ordered product, the respective order has to be allocated. As the restrictions of order allocation depend on the product configuration, they can only be assured if the product configuration is already fixed. Otherwise the uncertainty of configurations has to be taken into account when allocating orders. The point in time of fixing the product configuration of a customer order is referred to as "order freeze" in literature [19].

The point of time when fixing the configuration regarding a specific module can be no later than the module lead time before it is assembled to the product. The module lead time includes time for ordering the module and, if necessary, additional time for verifying the interfaces of the module with others. If the module lead times are not respected, it cannot be assured that the modules are physically present when they should be assembled to the ordered product. As the module lead times may be different for different modules, the order freeze can take place not at one single point in time for all modules, but for each module at another point in time also being referred to as distributed order freeze [20].

Module group	Alternative modules	Module lead time [days]	Production time [hours]
M1	M1.1	12	5
	M1.2	10	3
	M1.3	9	2

Fig. 3. Just in time specification of product option as an example of co-definition of product structure and production network

In each module group consisting of alternative modules, each module may require a different module lead time defining the distributed order freeze as illustrated in figure 3.

Module lead times have to be given with respect to each possible allocation of an order to an assembly plant. The time for assembling a specific module may also be different for alternative modules depending on the selected plant or even the selected line for assembly and is given as production time.

As the example illustrates, the modules are the basis for the co-definition of product structure and production network. The customer selects modules when configuring his product and therewith has to take into account supplier-specific lead times. The selection of modules restricts the allocation of the customer order and determines the assembly workload taking into account the production time for assembling the modules. Moreover, the customer could also receive information about the production status after the product configuration such as if a module has already been delivered by the respective supplier and if a module has already been assembled.

A consequence of this approach is that frugal problematics can be regarded as a combination of decision-making processes. Therefore, additional categories of information should be embedded in the product module concept for the implementation of the modular-based approach for the frugal strategy. These decision features related to the modules are not the traditional technical ones, but support customer involvement, knowledge reuse, as well as co-evolution of product structure and production strategy. For instance, supplier selection is a decision-making process based on requirement features that need the analysis of modules' importance (criticality), performance, cost tolerance, acceptable time to delivery, etc. Fixing a product module individually based on its lead time is a decision-making that requires the analysis of the product structure, the purchase process as well as the assembly process of modules. Decision features like time of involvement of the module in the assembly process and dependence with other assembly operations should be considered for this issue.

5. Conclusion

A new modular-based approach for co-defining product structure and production network has been introduced. The approach enables a close interaction of customers with product development and production network planning. Through the close interaction, frugality objectives can be achieved and customers can be integrated in the order fulfilment process providing flexibility to configure products just in time. Depending on the selected product modules, orders are allocated to respective final assembly facilities and modules are ordered from respective suppliers.

Being developed in the project "ProRegio" the approach will be prototypically implemented together with industrial partners in domestic appliances and aircraft industries as well production plant design. Thus, its feasibility and potential can be demonstrated.

Acknowledgements

The presented results were conducted within the project "ProRegio" entitled "customer-driven design of product-services and production networks to adapt to regional market requirements". This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement n° 636966. The authors would like thank the industrial partners involved in this research.

References

[1] Agarwal N, Brem A. Frugal and Reverse Innovation: Literature Overview and Case Study Insights from a German MNC in India and China. 18th International Conference on Engineering, Technology and Innovation. Munich, Germany; June 2012: 18-20.

[2] Knapp O, Zollenkop M, Durst S, Graner M, Think Act: Frugal Products. Roland Berger Strategy Consultants Publishing, June 2015.

[3] Zeschky M, Widenmayer B, Oliver, G. Frugal Innovation in Emerging markets: The case of Mettlet Toledo. Research Technology Management 2011; 54(4): 38–45.

[4] Tiwari R, Herstatt C. Frugal Innovation: A Global Networks' Perspective. Swiss Journal of Business Research and Practice 2012; 3: 245-274.

[5] Tolio T, Ceglarek D, ElMaraghy H.A, Fischer A, Hu S.J, Laperrière L, Newman S.T, Váncza J. SPECIES—Co-evolution of products, processes and production systems. CIRP Annals - Manufacturing Technology 2010; 59(2): 672–693.

[6] Cheraghi S.H, Dadashzadeh M, Subramanian M. Critical Success Factors For Supplier Selection: An Update. Journal of Applied Business Research 2004; 20(2): 91-108.

[7] Sako M. Modularity and outsourcing: The nature of co-evolution of product architecture and Organisation architecture in the global automotive industry. (Book chap) *In:* The business of systems integration. Oxford University Press, New York; 2005. p. 229-253.

[8] Jiao J, Tseng M.M. Fundamentals of product family architecture. Integrated Manufacturing Systems 2000; 11(7): 469 – 483.

[9] Ulrich K.T, Eppinger S.D. Product Design and Development, McGraw-Hill. 3rd edition New York, NY; 2004.

[10] Jiao J.R, Simpson T.W, Siddique Z. Product family design and platform-based product development: a state-of-the-art review. Journal of Intelligent Manufacturing 2007; 18: 5–29.

[11] Hubka V, Eder E.W. Theory of technical systems. 2nd ed. Springer-Verlag; 1998.

[12] ElMaraghy H, Schuh G, ElMaraghy W, Piller F, Schonsleben P, Tseng M, Bernard A. Product Variety Management. CIRP Annals in Manufacturing Technology 2013; 62(2): 629–652.

[13] Sosa M.E, Eppinger S.D, Rowles C.M. The misalignment of product architecture and organizational structure in complex product development INSEAD Working Paper; 2003/68/TM.

[14] Du X, Tseng M.M, Jiao J. Product Families for Mass Customization: Understanding the Architecture. The Customer Centric Enterprise Springer-Verlag: Berlin; 2003.

[15] Bruun H.P.L. PLM support to architecture based development contribution to computer-supported architecture modelling. PhD Thesis, DTU Mechanical Engineering, Technical University of Denmark; 2015.

[16] Coe NM, Dicken P, Hess M. Global Production Networks: Realizing the Potential. Journal of Economic Geography 2008; 8(3): 271–291.

[17] Meyr H., Wagner M., Rohde J. Structure of Advanced Planning Systems, in *Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies*, Springer-Verlag, Berlin Heidelberg; 2015; p. 99-106.

[18] Dörmer, J. Produktionsprogrammplanung bei variantenreicher Fließprodution: Untersucht am Beispiel der Automobilendmontage, Springer Gabler, Berlin; 2013.

[19] Volling T., Matzke A., Grunewald M., Spengler T. S. Planning of capacities and orders in build-to-order automobile production: A review, in European Journal of Operational Research 224, 2013; p. 240-260.

[20] Lanza G., Bürgin J., Berger D., Peters S. Wie Industrie 4.0 die Steuerung von Produktion und Supply Chain verändern wird. In: Horváth, P., Michel, U., eds. Controlling im digitalen Zeitalter: Herausforderungen und Best-Practice-Lösungen. Stuttgart; 2015; 87-99.