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Towards a Decision-Making Framework for Multi-Criteria Product Modularization in Cooperative Environments

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Abstract

Modular product family design is a strong strategy to offer a wide range of product variants economically. Many methods for designing and assessing modular product concepts are provided in literature - deciding between modular product structure alternatives, however, is still a challenging task, because of the many and unforeseeable effects on all product life-phases in combination with the high number of involved stakeholders. In addition, modularity alternatives cause multi-dimensional trade-offs that make the decision process a complex challenge.
Current approaches to decide the product modularization tend to focus on the prediction of either internal or external consequences. Furthermore, they rarely consider the prevalent situation of a company's internal tier structure with different organizational sections, responsible for different module design and supply.
In this paper, we investigate modularity decision problems and introduce an innovative framework and modularity decision dashboard, considering internal and external variety evaluation, conflicting objectives of stakeholders as well as company-internal tier structures of component, module and product suppliers. The approach builds on the integrated PKT-approach for developing modular product families, recent findings in complexity cost evaluation, effects of modularization and modularity decision problems. An industrial application at a modularization strategy project in an international powertool company is presented and proves basic validity of the framework and the process model. The results of the study demonstrate how an applicable modularity decision dashboard can facilitate cooperative decision-making and leads to a balanced variety for the electromotor module portfolio in an industrial environment.

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Keywords: Modular design; Decision making; Dashboard

1. Introduction

Companies are today faced with an increasing demand for product variety. One successful strategy to encounter this is to develop modular product structures (MPS). By using MPS, companies are able to provide a broad external variety while keeping their internal variety low. A broad and well-defined external variety leads to a better fit between customer needs and offers [1]. Internal variety is the variety of components, assemblies and processes during the creation of products [2]. Low internal variety has certain benefits, such as decreased product cost, process cost and complexity cost.

Product development usually provides different alternatives for engineering problems. Choosing a MPS alternative needs to be done early in a development project, has far-reaching consequences for all product life-phases and becomes a major challenge during the development process.

As shown in Fig. 1, organizational units that are close to customers and markets try to maximize the variety offered to customers. A close-to-market department (e.g. product management, sales) accordingly strives for an increasing variety in decision situations. Likewise, company-internal tiers (departments that are responsible for the development of modules) try to develop modules that meet requirements from external variety and hence strive to maximize the variety of

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modules. Ideally, modules meet exactly the requirements of target products. At the same time, these organizational units try to find the lowest possible number of modules and components, since development units underlie limited resource capabilities. Modules in turn consist of components of which the variety is desired to be low. A low component variety lowers complexity cost, reduces efforts in communication, or development expenses. This leads to decision-making with stronger focus on variety minimization.

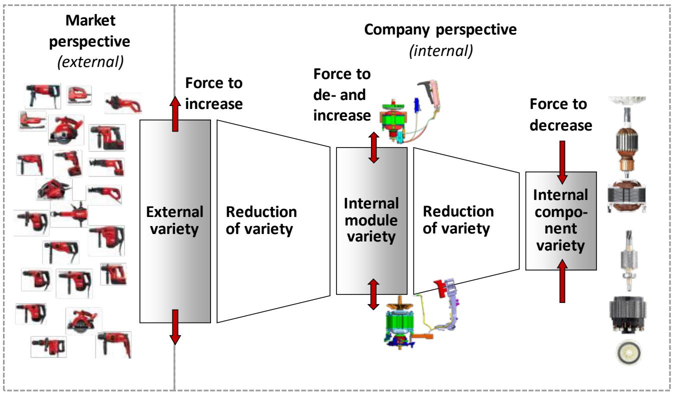

Fig. 1. The need for de- and increasing variety over company-internal tiers

The challenge for product development is to find the optimal variety for modules by balancing the trade-offs triggered by the three forces (Fig. 1) influencing the variety of the portfolio. The needs for a de- or increasing variety lead to conflicting objectives and trade-offs for different alternatives of MPS.

In this paper, we approach this problem by a new developed method, including a framework and corresponding process on modularity decision-making. Furthermore, we show the prototype of an innovative Modularity Decision Dashboard, combining different perspectives, structural aspects and modularity performance indicators. An industrial application shows how the approach influences cooperative decision-making in an industrial environment.

2. Research approach

To encounter this problem, we analyzed relevant literature and compared it to the needs of an MPS decision problem to identify insufficiencies of current approaches and possible contributions to a solution framework (Fig. 2).

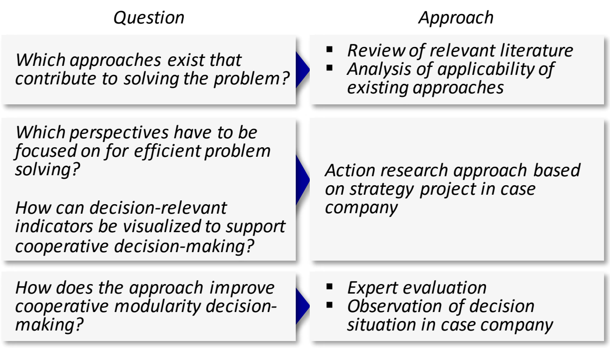

Fig. 2. Research approach

The data model, on which the framework bases, is derived from identified effects of modularity alternatives in earlier studies [3]. The framework is developed by an action research approach at a case company. The case company, Hilti Corporation, provides solutions for the construction industry and has 25.000 employers. The structure of its products (powertools) show distinct modular properties. Hilti utilizes a matrix organization for the module development of electrical drive systems, which has the responsibility of the internal module variety (middle column in Fig. 1).

The research addresses the question, which perspectives have to be included to meet the needs of different company-internal tiers. Moreover, how relevant data can be visualized in a cooperative decision-making process in order to foster information processing between participants. Thus, we opted for a case study in where a part of a module portfolio was defined by a single modularity decision. By this decision, the variety of the motor module portfolio was determined and thus had significant consequences for the target powertool portfolio. The succeeding evaluation of the framework and the dashboard prototype was done by expert interviews and by observations of meetings in which decisions were made.

3. State of the art

To give a support in MPS definition, literature provides a broad range of assessment approaches for effects [4] of product structures, platforms and modular product structures.

The development of MPS can be supported systematically by various methods. [5] provide a comprehensive model of architecting steps (Fig. 3). The model shows a sequence of 13 generic tasks, combining various modular and platform design methods. The development of MPS is driven by multiple objectives. [6] distinguishes between product-strategic and technical-functional drivers for modularity.

The quantification and assessment of structural indicators,

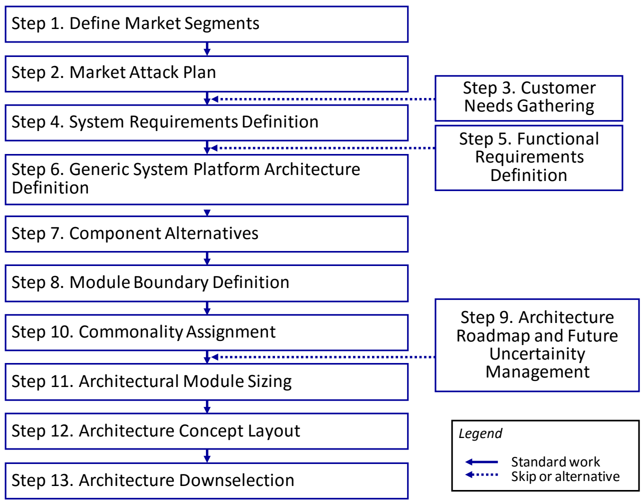

Fig. 3. Requirement flow down model of architecting steps [5]

which measure product architecture properties, can be supported by the measurement of e.g. commonality, complexity or indicators, which measure the independence of modules. The Platform Commonality Index [7], Total Constant Commonality Index [8] and the Degree of Commonality Index [9] are approaches that measure the variety, respectively, commonality of modular structure concepts. Another approach that focus on the measurement of product variety is given by [10]. Based on a Quality Function Deployment, the Generational Variety Index and Coupling Index is used to improve product platform architecture development. The measurement of complexity with respect to modularity can be supported by Complexity Indices [11]. The Independence of Cluster [12] metric enables the minimization of incidental interactions and thus increases product modularity. A recent work of [13] compares the coupling metrics for modules comprehensively.

Managerial requirements to address MPS selection problems focus on the economic assessment of modularization. Different costing techniques and their applicability are shown by [14], such as for assembly, product and production cost. A comprehensive controlling approach is the work of [15], which considers various cost effects in product development (such as lead-time, development expenses and capacity) as well as structural metrics (e.g. variant flexibility or recyclability). New approaches also focus on the effects caused by increasing complexity in companies. The effects of complexity induced by variety can be assessed with complexity cost metrics [16].

Taking not only technical indicators into account, several methods exist that consider aspects of markets and customers. The Power Tower according to [17] provides the segmentation of markets and the alignment of different product platforms. In terms of variety, [18] postulates a method to optimize product variety based on several input parameters. An approach to balance previously mentioned trade-offs caused by modularity is supported by the Product Variety Trade-off Chart [19]. The authors' approach compares the performance derivation (performance derivation index) and the non-commonality (non-commonality index) of different MPS alternatives. The method contributes to support the balance between the conflicting demand for higher commonality and performance. The approach is further extended by variety and commonality metrics by the recent work of [20]. Approaches combining aspects of external variety and sales perspectives are given by [21], [22] and [23]. [21] postulates a five-step approach for valuing product platforms, considering uncertainties and what-if-situations. Sales-related indicators, such as expected sales and sales revenue are assessed comparatively against necessary investments. A focus on the number of variants is given by [22] as they determine the number of platform variants against their profit. The Program Structuring Model [23] has a visual nature and models sales revenue and the number of units per levels across the product program. The approach is further implemented in the integrated PKT-approach [23].

More broad approaches focus on the management of product portfolios. A differentiated view on performance indicators from product architecture, supply chain, product program, finance and production is given by [24]. The portfolio approach as described by [25] considers planning purposes in product development. Hereby, the product project and idea-portfolio is assigned to different time domains. Being more focused on different stakeholder views, the Product Family Master Plan [26] brings customer, engineering and part view together. The approach follows a visual approach and aims to support the trade-off between variety and commonality. A more general perspective is the Portfolio Management approach [27], which focusses on the three aspects performance, strategy and context in terms of execution and market risk. [28] give a supporting method for evaluating product platforms via a multi-criteria scorecard approach. Hereby, indicators from different life-phases, such as product development, aftersales or service, are considered.

The most common assessment methods we have seen in our research are allocable to the product-strategic view on internal variety. Hereby, the effects of product structure concepts are assessed per indicators such as e.g. product cost, time to market or project expenses, as well as long-term flexibility of the module structures. In addition, the needs of decision makers are rarely considered, meaning that most approaches focus more on single aspects and insufficiently consider the different perspectives of involved stakeholders. Supplemental to the multi-perspectival principle and due to findings of recent literature [16] as well as the lack of its consideration in current practice [29], we propose to use additionally complexity cost techniques for a comprehensive MPS assessment.

4. Decision support framework for product modularization decision problems

In this chapter, we present a decision support framework and its corresponding process model to support cooperative modularization decision problems. The framework is based on the integrated PKT-Approach for Developing Modular Product Families [23] and the analysis of ten case studies of MPS decisions undertaken in two companies [3].

Aiming at closing the gap demonstrated in the last section, the framework considers aspects of variety and module tiers within a company and thus has a two-dimensional character (Fig. 4). The two dimensions are broken down further in three aspect areas each, covering the requirements of different tiers and hierarchical levels, which are relevant for decision-making (product, module and component).

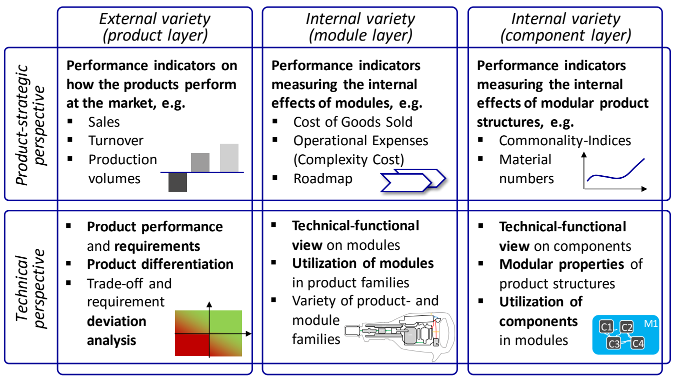

Fig. 4. Framework for MPS decision-making

Stakeholders with managerial positions tend to have a strategic perspective, whereby stakeholders developing a MPS have a focus on product structures and their corresponding technical and functional indicators. Aforesaid stakeholders which are closer to markets or customers have an external perspective on decision problems, checking the match between offered external variety and customer needs as well as possible mismatches between product properties and requirements. Departments from earlier product life-phases, such as e.g. product development, have a focus on aspects related to internal variety and its effects.

In the context of developing modular product families, the framework refers to step 13 "architecture down-selection" within the architecting flow-down model (Fig. 3, [5]). To apply the framework in cooperative decision-making for MPS, a corresponding process model is designed to guide trough a selection process of MPS alternatives. The generic process consists of four major steps, whereas step 2 is subdivided into six steps (Fig. 5).

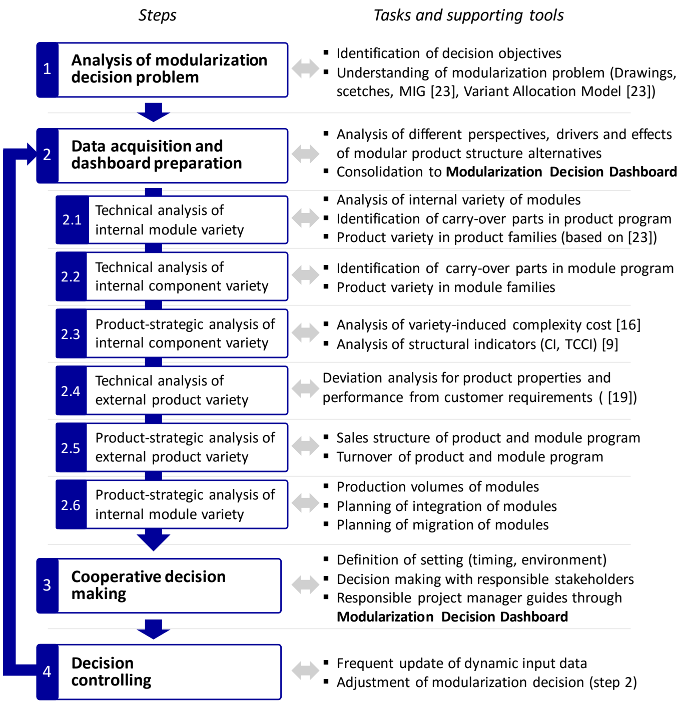

Fig. 5. Process for cooperative modular product structure decision-making

In step 1, the modularization selection problem is analyzed, meaning that objectives to be fulfilled by the decision, affected products, modules and components, are identified. This step is supported by visualization techniques, such as drawings, CAD models or reduced illustrations of MPS via the Modular Interface Graph (MIG) [23].

Once the decision problem is understood, relevant data of the MPS alternatives is acquired and visualized through a Modularization Decision Dashboard (step 2). Visualizations as tools in product development offer unique functionalities over other kinds of design support tools [30]. They foster decision processes especially with interdisciplinary character [23]. To ensure a systematic acquisition, step 2 further describes the tasks of each of the six focal areas (Fig. 4). In step 2.1 the variety of modules and products is analyzed with respect to criteria which is relevant for company-internal customers of the modules. The analysis of internal component variety from a structural point-of-view is done in step 2.2. To ensure a most precise determination, data from bill-of-material (BOM) is used. After the structure of the product and module family is illustrated, step 2.3 treats structural indicators, such as e.g. TCCI [8], to give a relative comparison. Based on the technical properties of the components and modules, a detailed assessment of the fitting between the target products and modules is conducted in step 2.4. The product properties that change over different MPS alternatives are assessed in step 2.5. This includes the customers' focal needs and how they are affected by the alternatives. This means e.g. that by different modular boundaries, a product family might get a different weight, performance, or size. Based on [19], relevant trade-offs regarding customer requirements are analyzed for each alternative. After identifying the influence on customer-relevant properties, experts from engineering and sales can assess whether the deviations influence the market performance of affected products or not. In step 2.6, the numbers are used in order to determine potential changes in production numbers of different modules. To conclude the assessment, a module migration and integration plan (MMIP) is set up to harmonize product and module roadmap.

The actual decision is made in step 3. Since product modularization affects multiple domains and multiple criteria, relevant stakeholders from different domains, hierarchical levels as well as from different life-phases are included and discuss in a workshop-based approach the effects resulting from the different modularity alternatives. The robustness of the recommendation is verified by a sensitivity analysis of the input data. After an alternative is chosen, the controlling of the decision follows in step 4. Hereby, the owner of the decision adjusts the input data in an appropriate frequency over time.

5. Application of the framework and Modularization Decision Dashboard in an industrial case study

To prove a basic empirical evidence, we tested the framework and a prototype of the Modularity Decision Dashboard (Fig. 6) in a modularization strategy project for motor module variants for powertools at Hilti. The approach was applied on a decision situation with far-reaching consequences for the product and module program. The project was facing a mayor selection decision of different modularization alternatives in a conceptual portfolio design phase. The four most relevant of these alternatives are considered in this study. The modular concepts were initially driven by two aspects. Alternative concept A was especially designed to have the lowest reasonable variety of motor modules. Due to possible trade-offs regarding performance and requirements for several products, alternative concept B was developed. In order to give decision makers a better insight on how the concepts perform, two extreme alternative concepts are included. One concept with maximized variety (V_{max}) means that each product gets its exclusively developed module. The other extrema (V_{min}) is to develop one module variant for all regarded products. By this concept, one material number occurs.

The design of the dashboard was supported by a methodical process for developing visualizations as tools in product development [31]. During the study, the functional goal of the visualizations, the process itself including necessary data and information, as well as the individual roles involved in the decision-making process, were recorded and analyzed. The prototype in Fig. 6 focusses on alternative B, whereas the fields F3, F4 and F9 compare all alternative concepts. The properties of other alternatives (A, V_{min} and V_{max}) are shown in different layers of this prototype. The later computer-aided dashboard supports a switch between the layers by clicking in the dashboard. As shown in field F1 via a variety tree, the

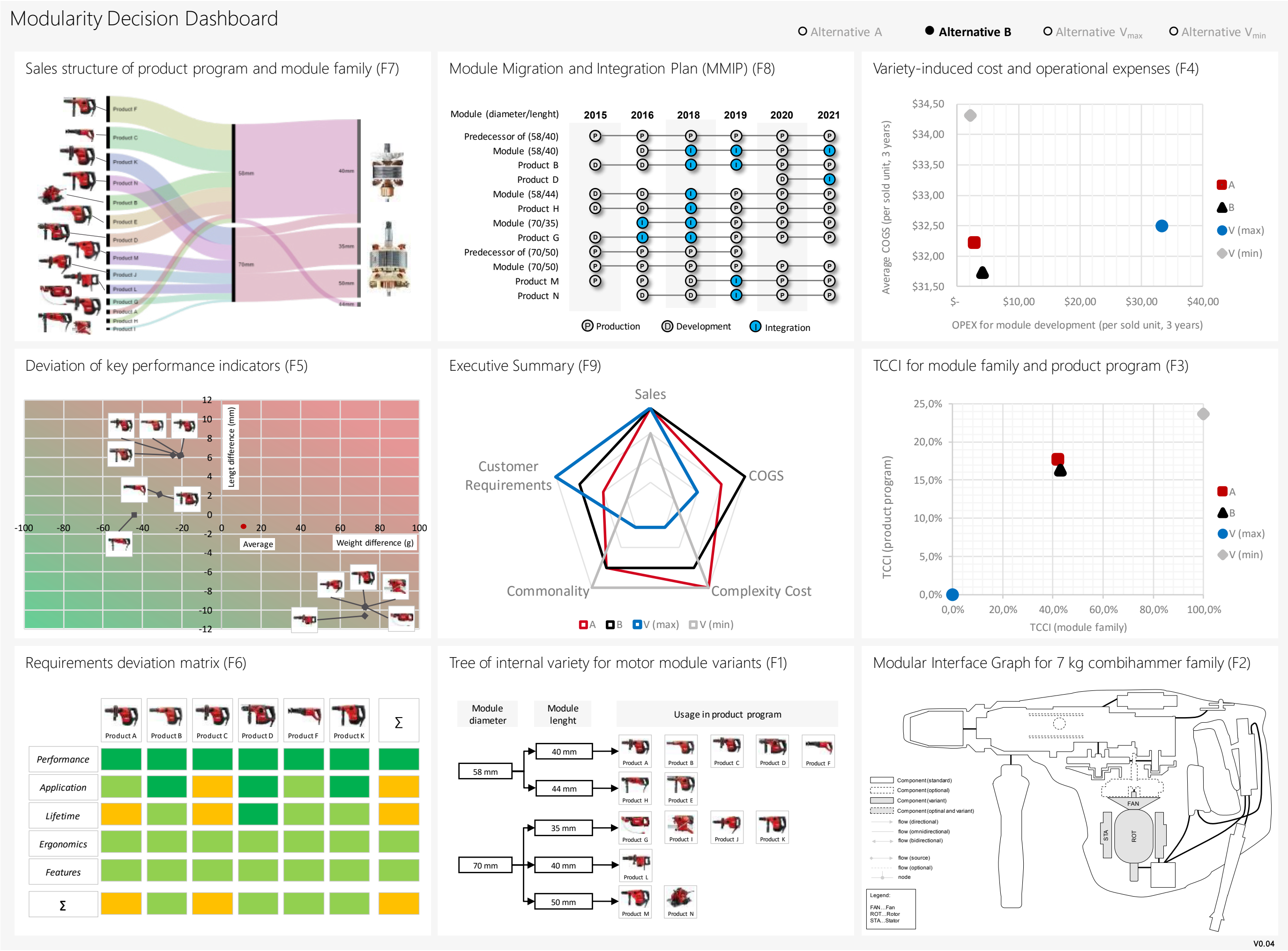

Fig. 6. Prototype of Modularization Decision Dashboard

alternative concept B consists of two motor module variants (diameter 58 mm and 70 mm) for the shown scope of products (step 2.1). Field F2 (step 2.2) shows the impact of alternative B on the variety of a product family. The next step (step 2.3) determines the commonality (field F3) and resulting complexity cost of all four alternatives (field F4). Using TCCI, alternatives A and B are similar in terms of variety of the module family (ΔTCCI = 0.011) and the variety of the product program (ΔTCCI = 0.015). The material numbers do not vary significantly for the alternatives over the product program (correlation r = 0,916). Thus, the induced complexity cost for cost of goods sold (COGS) and for operational expenditures (OPEX) are determined (field F4). The analysis shows that both extreme scenarios V_{min} and V_{max} result in higher cost (COGS and OPEX). Concept A is at $2.78, concept B at $4.17 OPEX allocated to sold units. For COGS, concept A is at $32.23, concept B at $31.73 per unit.

In step 2.4, the external variety of the products is regarded from a technical perspective. The analysis is visualized in field F5, where the diverging product properties are visualized in two-dimensional graphs.

Field F6 shows the deviation of each products' value proposition. By having a detailed assessment of products and module properties, experts from sales and product management are able to predict a possible influence on sales and thus of module share (field F7). We allocate the products to module variants via an Alluvial diagram, whereas the volume distribution is represented by the height of the columns. Based on the overview in F5 and F6, the experts estimate no impact on the sales structure of all target products that are in scope. As a last step (field F8), the MMIP illustrates how modules are integrated into target products. The consolidated results are shown in the executive summary (field F9). The properties of the alternative concepts are summarized and assessed according to their performance. With respect to the different disciplines, the summary shows that only alternative A and B have satisfactory impact on the target dimensions. However, concept B has a more desired impact on COGS and requirements. During the discussion, the fields F1 and F2 were used to explain the problem to decision makers. For the assessment, field F4 and the impacts of field F5 and F6 on F7 were discussed intensely. F8 was discussed repetitively in order to ensure the alignment between product and module roadmap. Taking all the data of the modular concepts into account, the decision was made to choose alternative B.

6. Conclusion

We present a new-developed decision-making framework and procedure for product modularization decision-making in cooperative environments. The method encounters deficiencies of existing approaches with a comprehensive assessment of MPS, by means of recent findings in modular design research and the consideration of different stakeholder perspectives. The method has been applied to an industrial decision problem. Hereby, a modularity concept was decided by guidance of the dashboard included in the methodical approach. In contrast to current practice in decision-making processes, the decision was based on differentiated perspectives rather than on singe indicators (e.g. manufacturing cost). By using the dashboard, the decision tended towards a balanced solution, thus not the solution with the lower variety was chosen. Hence we conclude that visualizations of different performance indicators from different product life-phases improve the decision quality in the context of cooperative MPSA decision-making.

Overall, the application of the framework and the Modularization Decision Dashboard brought the expected results. We could observe that especially the simultaneous utilization of different visualized indicators fosters information processing and thus improves communication between participants. The deficiencies of decision makers, as postulated by descriptive decision theories, can thus be encountered by the approach. This positive feedback of engineers, project and general management supports the basic validity of the concept to facilitate cooperative decision-making. Case accessibility and scientific integrity were satisfactory, albeit so far, the findings are limited to the case company.

Future research will focus on the descriptive application of the method in other decision situations. In a subsequent step, the approach shall be applied in another company, which follows an engineer-to-stock strategy. These findings will contribute to a deeper understanding of how decision processes work and how they are influenced by participating stakeholders. Furthermore, this research will generate deeper knowledge about relevant effects of modularity in the context of behavioral decision-making for MPS definition.

References

[1] B. Kahn, “Variety: From the consumer’s perspective”, in H. Teck-Hua, C. Tang, “Product Variety Management”. New York, Springer, 1998.

[2] H. J. Franke, N. Firchau, J. Hesselbach, B. Huch, „Variantenmanagement in der Einzel- und Kleinserienfertigung“, Hanser, Munich, 2002.

[3] M. Windheim, E. Greve, D. Krause, “Decisive Economies and Opportunity Cost of Modular Product Structure Alternatives: An Empirical Case Study”, IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE, 2017.

[4] P. Harland, Z. Uddin, “Effects of product platform development: fostering lean product development and production”, International Journal of Product Development, vol. 19 (5), 2014, pp. 259-285.

[5] K. Otto, K. Hölttä-Otto. T. Simpson, D. Krause, S. Ripperda, S. Moon, “Global Views on Modular Design Research”, Journal of Mechanical Design, vol. 138 (7), 2016.

[6] G. Erixon, “Modular function deployment”, Dissertation, The Royal Inst. of Technology, Stockholm, Sweden, 1998.

[7] Z. Siddique, D. Rosen, “On the applicability of product variety design concepts to automotive platform commonality”, Proceedings of Design Engineering Technical Conferences – ASME/DECT’98, Atlanta, 1998.

[8] J. Wacker, M. Treleven, “Component part standardization: An analysis of commonality sources and indices“, Journal of Operations Management, vol. 6 (2), 1986, pp. 219-244.

[9] D. Collier, “The Measurement and Operating Benefits of Component Part Commonality“, Decision Sciences, vol. 12 (1), 1981, pp. 85-96.

[10] M. Martin, “Design for Variety: A Methodology for Developing Product Platform Architectures“, Dissertation, Stanford University, Department of Mechanical Engineering, Stanford, 1999.

[11] M. Martin, K. Ishii, “Design for Variety: Development of complexity indices and design charts”, ASME Design Engineering Technical Conferences (DETC), Sacramento, USA, 1997.

[12] P. Newcomb, B. Bras, D. Rosen, “Implications of Modularity on Product Design for the Life Cycle“, JMD, vol. 120 (3), 1998, pp. 483-490.

[13] K. Hölttä, “What Do Coupling Modularity Metrics Measure?”, ICADRE14, Singapore, 2014.

[14] S. Fixson, “Assessing Product Architecture Costing: Product Life Cycles, Allocation rules, and Cost Models”, DETC’04 ASME 2004 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Salt Lake City, 2004.

[15] A. Ericsson, G. Erixon, “Controlling design variants: Modular product platforms”, ASME press, New York, 1999, pp. 145.

[16] S. Ripperda, D. Krause, “Cost Effects of Modular Product Family Structures: Methods and Quantification of Impacts to Support Decision Making “, Journal of Mechanical Design, vol. 139 (2), 2017.

[17] M. Meyer, A. Lehnerd, “The Power of Product Platforms: Building Value and Cost Leadership”, New York, NY: The Free Press, 1997.

[18] K. Fujita, “Product Variety Optimization“, in: Simpson T., Siddique Z., Jiao J., Product platform and product family design. Methods and applications, Springer, New York, 2006, pp. 186-223.

[19] T. Simpson, C. Seepersad, F. Mistree, “Balancing Commonality and Performance within the Concurrent Design of Multiple Products in a Product Family," Concurrent Engineering Research and Applications, 2001, vol. 9 (3), pp. 177-190.

[20] S. Jung, T. Simpson, “An integrated approach to product family redesign using commonality and variety metrics”, Research in Engineering Design, vol. 27 (4), 2016.

[21] S. Kidd, “A systematic method for valuing product platform strategy”, Dissertation, Massachusetts Institute of Technology, 1998.

[22] O. de Weck, E. Suh, D. Chang, “Product Family and Platform Portfolio Optimization“, ASME Proceedings of DETC’03, Chicago, 2003.

[23] D. Krause, G. Beckmann, S. Eilmus, N. Gebhardt, H. Jonas, R. Rettberg, “Integrated Development of Modular Product Families”, in T. Simpson, J. Jiao, Z. Siddique, K. Hölttä-Otto, “Advances in Product Family and Product Platform Design”, New York, Springer, 2014, pp. 245-269.

[24] G. Schuh, S. Rudolf, T. Vogels, “Performance measurement of modular product platforms”, Proceedings of the 47th CIRP Conference on Manufacturing Systems, 2014.

[25] F. Larsson, “Managing the new product portfolio”, Dissertation, Technical University of Denmark, Lyngby, 2007.

[26] U. Harlou, “Developing product families based on architectures“, Dissertation, Technical University of Denmark, Lyngby, 2006.

[27] S. Petersen, M. Steinert, S. Beckmann, “Design Driven Portfolio Management“, Proceedings of the 18th International Conference on Engineering Design (ICED 11), Lyngby/Copenhagen, Denmark, 2011.

[28] K. Hölttä-Otto, K. Otto, “Platform Concept Evaluation”, in T. Simpson, Z. Siddique, J. Jiao, “Product Platform and Product Family Design”, New York, Springer, 2006, pp. 49-72.

[29] M. Windheim, J. Hackl, N. Gebhardt, D. Krause, “Assessing Impacts of Modular Product Architectures on the Firm: A Case Study”, 14th International Design Conference, Dubrovnik, 2016, pp. 1445 - 1454.

[30] N. Gebhardt, T. Bahns, D. Krause, “An Example of Visually Supported Design of Modular Product Families“, Procedia CIRP, 2014, pp. 75-80.

[31] N. Gebhardt, D. Krause, “A Method for Designing Visualisations as Product Development Tools”, 14th International Design Conference, Dubrovnik, 2016, pp. 611-62.