Transdisciplinary Engineering: Crossing Boundaries
M. Borsato et al. (Eds.)

doi:10.3233/978-1-61499-703-0-35

Assessing Producibility of Product Platforms Using Set-Based Concurrent Engineering

Jonas LANDAHL[a,1], Christoffer LEVANDOWSKI[a], Hans JOHANNESSON[a], Ola ISAKSSON[a,b]
[a] *Chalmers University of Technology, Gothenburg, Sweden*
[b] *GKN Aerospace Sweden AB, Trollhättan, Sweden*

Abstract. This paper presents a method to facilitate model-based producibility assessments of product variants in the early phases of platform development. The approach uses set-based concurrent engineering principles to explore and narrow down a design space towards feasible alternatives. A case including *tool accessibility* and *assembly robustness* of an aerospace sub-system platform is used to demonstrate the approach. The assessment activities can be prepared in parallel, and support the concurrency needed, across design and manufacturing, to serve improved process efficiency. Ultimately, the approach may reduce late design modifications thanks to increased reuse of manufacturing knowledge, as well as reduce cost thanks to less physical prototyping and testing.

Keywords. integrated platform development, product platforms, manufacturing platforms, producibility assessments, set-based concurrent engineering

Introduction

Research on platforms typically aim to understand how scale benefits in production can be met, using a low number of manufactured parts [1]. However, the industrial need and the direction of research points at increased support for reuse in the development phases [2]. A prevailing concern for such a course is the risk of overlooking manufacturing aspects. In the pursuit for a feasible producible product family, there is a need to reduce time-consuming and costly physical verification and better assess the producibility of the platform, and the family of variants derived from it. In the same way as product concepts can be explored, production concepts can be explored simultaneously. In light of this concurrency, producibility refers to the relative effort needed to produce products with respect to available technology.

Computer Aided Engineering (CAE) tools can be used to simulate product performance, such as product life, as well as manufacturing capabilities, such as welding quality. Simulations are typically used for product performance verification, process planning and pre-production verification. In these late phases of the development, a design modification is more expensive compared to that of the conceptual phases of development. Being able to better assess multiple producibility

[1] Corresponding Author, E-Mail: jonas.landahl@chalmers.se

aspects on multiple design alternatives, and to assess them in concurrency can provide the efficiency needed to support design engineers in making cross-discipline design decisions [3]. In this way, a product family can be fit for desired manufacturing conditions early in the development and costly design modifications in the late phases of development can be reduced.

1. Research Approach

This paper introduces means to prepare platform assessment processes using improved process activities. Such platform assessment process can be used to assess producibility of product platform concepts. To illustrate the approach, a case from the aerospace industry is provided. The case is prepared as a part of a long running collaboration with GKN Aerospace Sweden AB. The purpose of using a real-life case is to validate the research in an industrial context and provide rigor to the research findings. By interviewing system specialists and examining relevant documentation, such as design guidelines and process descriptions, in-depth knowledge of products, manufacturing tools and equipment as well as process knowledge have been extracted. During workshops, system specialists and researchers have revised and refined models in collaboration. To propel the research provided in this paper, a research question is formulated: *how can producibility be assessed across the design space of a conceptual product platform?*

2. State-of-the-art

This section presents a body of research related to platform development of both products and manufacturing systems. It also gives an overview of producibility related to product and production development and how set-based concurrent engineering relates to platform development.

2.1. Product Platforms

Product platforms as a means of reusing design knowledge has been receiving significant attention over the past decade [1]. The corporate view of a product platform is a collection of physical parts that can be combined into distinctive products [4]. These physical parts, or modules, are created with a static set of customer requirements in mind. However, this view on platforms is sub-optimal for businesses where customers constantly demand new functionality, or where changes to the product are commonplace due to introduction of new requirements [5]. In brief, such platforms support a low number of parts in manufacturing, but provides little support in development [6]. To increase support in the development phases, there are other ways to maintain efficiency over time. For example, design reuse could encompass other things than physical parts. Alblas and Wortmann [7] suggest design reuse using function platforms. Function platforms enable reuse of functions as well as the configuration of a function family, rather than a part family. Levandowski et al. [8] propose using function modeling as a way to describe product platforms in the early phases of development to increase the ability to reuse.

2.2. Producibility of Product Platforms

There are several approaches to integrate manufacturing in design, such as Design for Manufacturing (DfM) and Design for Assembly (DfA). These approaches provide design engineers with guidelines on how to design products to be producible. Producibility links the functions, characteristics and performance of products together [9]. There are several examples of producibility aspects, such as tool accessibility in an assembly process and geometrical robustness [10]. However, producibility of product variants has received little attention, although some work has recognized the potential to integrate manufacturing platforms and product platforms. Such integration is discussed by Michaelis [11], among others. Michaelis describes how co-development of products and manufacturing systems can be accomplished using an integrated platform approach. As function models can represent designs, also manufacturing systems may be modeled in a similar fashion. By using manufacturing operations as connecting elements, the two disciplines can be linked [11]. Closely related to product and manufacturing platforms, Koren et al. [12] suggest reconfigurable manufacturing systems that can accommodate several product variants.

2.3. A Platform Model

To efficiently support design reuse in the development phases, platform models need to allow for modeling of both products and manufacturing systems during all phases of the platform development process. Claesson [13] developed the configurable component (CC) concept – a product platform model that was later extended to include manufacturing systems and manufacturing operations [11]. The model supports reuse of functional features, which is made possible through an object-oriented approach based on enhanced function-means (EF-M) modeling [14]. Variability is served through alternative design solutions, *the modular bandwidth*, and parametric ranges, *the scalable bandwidth*.

A platform based on the CC concept consists of a set of generic systems, each system described by one CC object. A CC object can describe for example an entire aircraft, a jet engine or welding equipment. Essentially, an architecture of CC objects does not represent merely one variant, rather every engine in the product platform or all welding equipment in the manufacturing platform. Thanks to the generic representation of the CC concept, compared to other platform approaches, the platform does not have to rely on fixed interfaces between systems to achieve concurrency. Instead, the interfaces between objects can be configured simultaneously, which leaves the design to be more flexible for longer time in the development.

There are several objects within a CC. The *DNA* of the CC, the design rationale (DR), describes a decomposition of the design and how each element of the CC fulfills a function. The DR is manifested as an EF-M tree, consisting of functional requirement objects (FRs), design solution objects (DSs) and constraint objects (Cs) [14]. Each object has a parameter set of variant parameters (VPs). The VPs define in what dimensions the CC object can vary, thus the ranges of the VPs determine the bandwidth of a CC object. The parameter set also provides information of how the parameters are distributed to the objects within the CC. To receive variant parameters (VPs) from other CCs, the control interface (CI) object is used. And to expose the VPs to other CCs, the composition set (CS) object is used. By assigning values to the VPs, a CC object can be configured into distinctive variants. The CC object is illustrated in Figure 1.

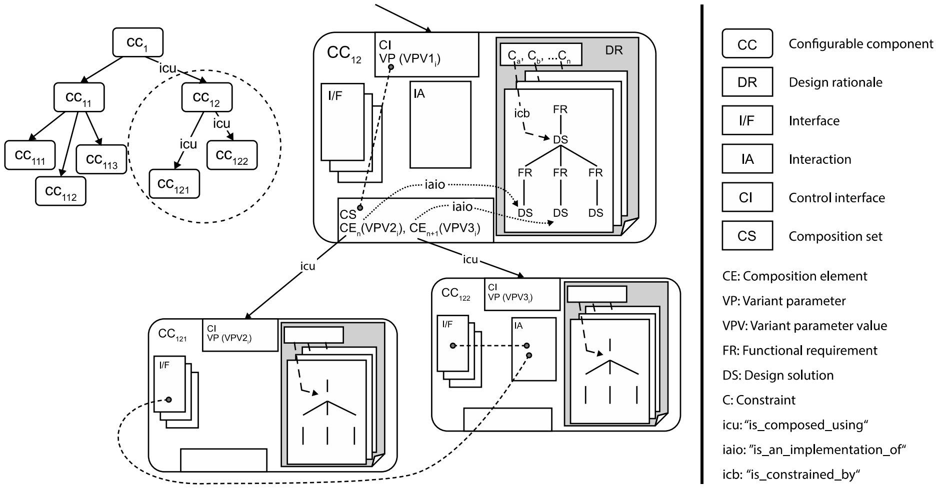


Figure 1. A configurable component, CC object (as drawn in [11], adapted from [13]).

2.4. Set-based Concurrent Engineering

Concurrent Engineering (CE) is a systematic approach to transdisciplinary development of products, manufacturing systems and supporting processes. CE is mainly seen as an organizational approach where processes can be made in concurrency, however they can also be reflected in how designs are modeled [6]. CE primarily emphasizes the early interchange of information that affect downstream activities, when the information is still preliminary [15].

In the early phases of development, contrary to point-based design, set-based advocates design space exploration, rather than selecting an arbitrary solution. Set-based concurrent engineering (SBCE) builds on three principles, 1) *mapping the design space*, 2) *integrating by intersection*, and 3) *establishing feasibility before commitment*. These principles advocate a sound depiction of a design and how it may vary due to changing functionality and requirements. Sobek et al. [16] summarize SBCE as *"reasoning, developing and communicating about sets of solutions in parallel and relatively independently."* SBCE can be applied to explore a wide variety of design alternatives that are systematically narrowed down by excluding inferior alternatives.

3. The Suggested Approach

In the early phases of development, it is inexpensive to explore the design space, test alternative solutions and consecutively eliminate unfeasible alternatives to find feasible product variants. However, to generate sufficient information about a set of design alternatives, an assessment process needs to be prepared. Thereto, suitable software systems must be chosen, and a PLM architecture to be established. In this case, such a PLM architecture revolves around a platform modeling and configuration tool, including platform models, to which CAE tools are linked and arranged to. A method to support design engineers in preparing such platform assessment processes is proposed.

3.1. Platform Assessment Process Blocks

To sufficiently prepare a platform assessment process, a standalone assessment process block is introduced. The process block builds on set-based concurrent engineering, to allow for exploring the design space as well as consecutively excluding inferior alternatives as new information becomes available. Preparing an assessment process block includes five steps. The steps are illustrated in Figure 2 and described below:

1) Define a trade-off parameter, to determine what to assess
2) Update the platform with design and manufacturing information, to allow for design reuse of functions, solutions and constraints. More details on this step is provided in [6,11]
3) Create or update parameterized conceptual 3D models using suitable software, to form a basis for more detailed visualization and simulations
4) Create or update a simulation model using an appropriate CAE software, to be able to generate new information about a set of conceptual design alternatives
5) Assign specific constraints, from the platform, onto the assessment process block, to exclude inferior alternatives as information becomes available

When several process blocks have been prepared, they can be arranged into a process to gain an aggregated and sound output as a basis for design decisions. The output of a platform assessment process is either no feasible alternatives, or a number of feasible alternatives. The former scenario leaves the design engineer with information of why there are no feasible alternatives. The latter scenario leaves the design engineer with trade-off information as a basis for comparison between a set of conceptual design alternatives. A platform assessment process with several process blocks is illustrated in Figure 3. An essential part of arranging the process blocks into a complete process is to ensure the information flow between the software systems, which is why a PLM architecture may be prepared to satisfy the need to interchange information between the software interfaces. An example of how to prepare such a PLM architecture that supports the platform assessment process blocks is provided in [3].

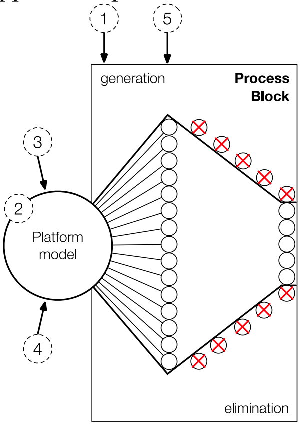


Figure 2. A platform assessment process block.

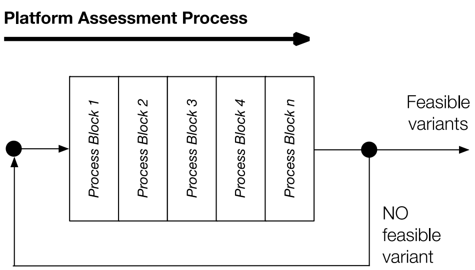


Figure 3. A platform assessment process .

4. Illustrative Case

The approach is illustrated using a case from the aerospace industry. The case company, GKN Aerospace Sweden AB, is a component supplier that designs and manufactures static parts for commercial jet engines. The studied product, Turbine Rear Structure (TRS), is located at the rear of the engine and is illustrated in Figure 4 and Figure 5. Each TRS is currently manufactured at a yearly volume of a few hundred units and is customized for different customers. The case company has the ambition to reduce the time from a customer request to an offer of feasible conceptual alternatives from three months to three weeks. To be equipped for such a scenario, an imminent concern is to incorporate knowledge about manufacturing in the platform concept development.

The TRS can be manufactured in various ways. This case illustrates a welding assembly scenario, which is why the TRS is divided into segments, shown in Figure 5. A new requirement is introduced. The engine need to endure higher operating temperatures. As a result of the new requirement, the thermal loads in the TRS will increase. To reduce the increased thermal loads, a solution is to lean the mid-section, shown in Figure 5. A set of lean angles is studied to find a feasible solution, and the producibility is concurrency explored across the design space.

To ensure producibility, *tool accessibility* and *assembly robustness* are assessed for the design alternatives encompassed by the platform, each with a discrete lean angle of the mid-section.

- *Tool accessibility*: There is a risk of machine disturbances due to collisions between the welding tool and work pieces, and the effects of the weld process when the pieces are welded together. Preliminary models of the TRS and weld characteristics are created to explore different accessibility alternatives.
- *Assembly robustness*: The position of the weld split line is critical for the assembly robustness. A simulation model is created to explore alternative positions of weld split lines, as the robustness of the different alternatives can be assessed.

A platform assessment process comprising of two assessment process blocks is prepared. The first process block concerns tool accessibility. The second process block concerns assembly robustness.

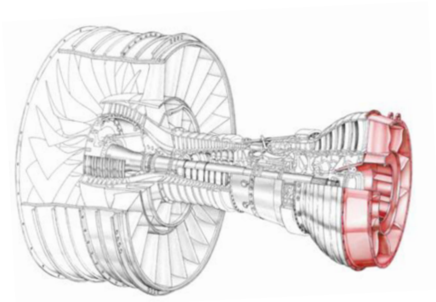


Figure 4. An aero engine with the TRS to the right [17].

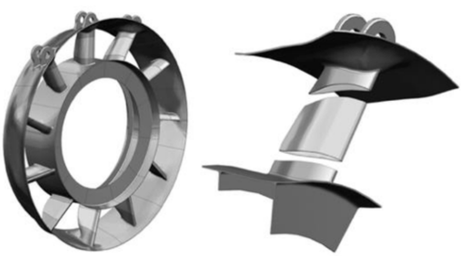


Figure 5. The TRS divided into segments, which are welded together in an assembly process.

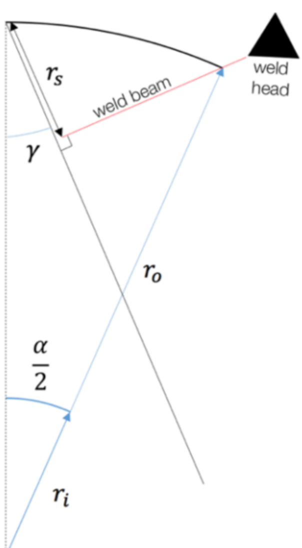
4.1. Process Block 1 – Assessment of Accessibility

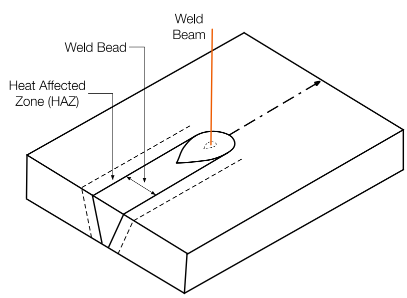
A trade-off parameter is defined: *tool accessibility* (binary measure: OK/NOTOK). In this case, the interaction between the weld beam and the TRS segment is analyzed. The case is represented by a model describing the relationship between design features and manufacturing knowledge. To better assess tool accessibility of a number of conceptual design alternatives, design principles and manufacturing knowledge are modeled in the platform system objects, provided in Figure 1, to be reused across the bandwidth of the platform.

The variant parameter (VP) r_s, shown in Figure 6, defines the constraining upper limit of the weld split line, to ensure that the weld beam will not interfere the with the outer ring of the TRS design. The same procedure is made for the inner ring. In this way a limiting area for the weld split line can be efficiently derived for each alternative across the design space. Through this, accessibility can be ensured.

By integrating the design and manufacturing solution spaces, the weld bead and the Heat Affected Zone (HAZ) are constraining the area for where the weld split lines are to be positioned to ensure accessibility. To ensure the quality of the welded product, the weld bead and the *HAZ* are not allowed to interfere with surrounding geometry, the weld beam shall be undisturbed until it meets the work pieces and the weld beam shall be perpendicular to the weld split line, see Figure 6 and Figure 7.

An integrated platform is prepared with the information provided above using the platform development software Configurable Component Modeler (CCM). CCM is an object-oriented modeling software which is based on the theory of EF-M modeling and the configurable component concept. By modeling a bandwidth of the VP *lean angle*, γ, a number of design alternatives is generated using CCM. The *outer radius*, r_o, the *inner radius*, r_i, and the *number of segments*, N, were held constant for pedagogical reasons. The results are provided in Table 1.





r_O – *radius* of the outer ring
r_i – *radius* of the inner ring
N– *number of segments* in a full ring
α – *angle* that defines the segments $\alpha = \left(\frac{360}{N}\right)$
γ – *lean angle* of the middle segment
r_s – *constraining distance* for weld beam

$$r_s = r_o\left(cos(\gamma) - cos\left(\gamma + \frac{\alpha}{2}\right)\right)$$

Figure 6. To the left; a preliminary 2D model a TRS segment, in the bottom right; the relationships between the VPs of the preliminary 2D model, and in the top right; a schematic model of a weld beam in interaction with work pieces with welding characteristics.

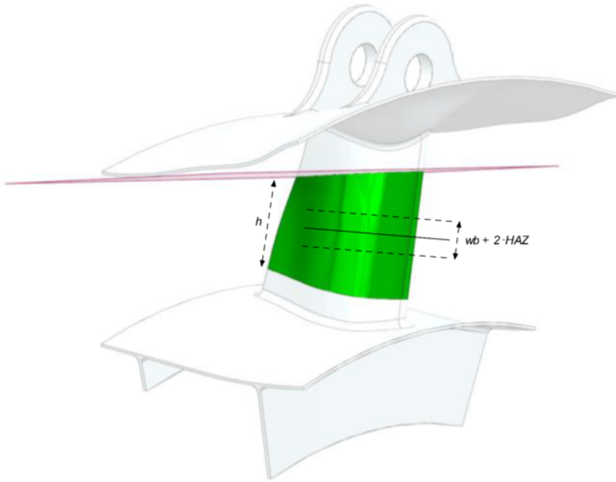


Figure 7. A preliminary 3D model of a TRS segment, depicting the constraining VPs for determining the welding accessibility.

Table 1. A binary measure of accessibility (OK/NOTOK) can be generated based on the preliminary information.

Variant [number]	**Outer Radius, r_O / Inner Radius, r_i** [mm]	**Lean Angle, γ** [°]	**Weld Area Height, h** [mm]	**Manufacturing constraint** [mm] $h < wb + 2 \cdot HAZ$	**Accessibility** [OK/NOTOK]
1	680 / 450	0	107	h > 70; OK; NOTOK	OK
2	680 / 450	1	104	h > 70; OK; NOTOK	OK
3	680 / 450	2	101	h > 70; OK; NOTOK	OK
4	680 / 450	3	98	h > 70; OK; NOTOK	OK
5	680 / 450	4	95	h > 70; OK; NOTOK	OK
6	680 / 450	5	92	h > 70; OK; NOTOK	OK
7	680 / 450	6	89	h > 70; OK; NOTOK	OK
8	680 / 450	7	86	h > 70; OK; NOTOK	OK
9	680 / 450	8	83	h > 70; OK; NOTOK	OK
10	680 / 450	9	80	h > 70; OK; NOTOK	OK
11	680 / 450	10	77	h > 70; OK; NOTOK	OK
12	680 / 450	11	74	h > 70; OK; NOTOK	OK
13	680 / 450	12	71	h > 70; OK; NOTOK	OK
14	680 / 450	13	68	h > 70; OK; NOTOK	NOTOK
15	680 / 450	14	65	h > 70; OK; NOTOK	NOTOK
16	680 / 450	15	62	h > 70; OK; NOTOK	NOTOK
17	680 / 450	16	60	h > 70; OK; NOTOK	NOTOK
18	680 / 450	17	57	h > 70; OK; NOTOK	NOTOK
19	680 / 450	18	54	h > 70; OK; NOTOK	NOTOK
20	680 / 450	19	51	h > 70; OK; NOTOK	NOTOK

4.2. Process Block 2 – Assessment of Assembly Robustness

A 3D geometry of the TRS segment, and the preliminary verification of accessibility is the output from *Process Block 1*, and the input to *Process Block 2*.

A trade-off parameter is defined: *assembly robustness* (binary measure: OK/NOTOK). The platform model is updated with a constraint, in this case a sensitivity measure RMS (Root Mean Square). Thereafter, a simulation model is created in a CAE software tool (RD&T). By applying the process block, a set of weld split lines and the sensitivity measure (RMS) for each weld split line can be generated. The less sensitive the alternative (low RMS value), the more robust the assembly. Two alternative weld split lines are provided and can be seen in Figure 8. More details on how to prepare this simulation model is provided in [10]. The lowest tolerated RMS is modeled in the platform and is assigned to *Process Block 2* to exclude inferior weld split lines as the simulation is executed.

The result of the simulation is provided in Table 2 can be made for all the conceptual alternatives provided in Table 1. In this way, it is possible to further explore the producibility across the design space, within the tool accessibility constraints provided in *Process Block 1*.

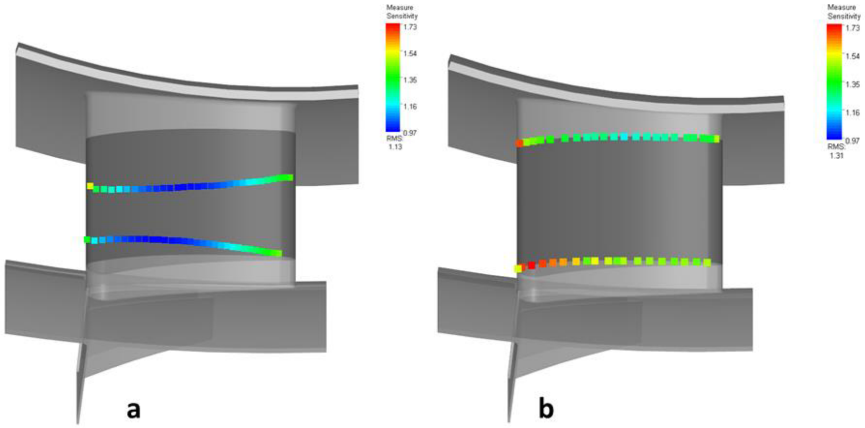


Figure 8. Two different alternatives of weld split lines (a and b), and their welding robustness [10].

Table 2. Binary measure of assembly robustness (OK/NOTOK), generated based on simulations

Variant [number]	**Accessibility** [OK/NOTOK]	**Sensitivity,** *RMS* [RMS]	**Sensitivity Constraint** [RMS]	**Assembly Robustness** [OK/NOTOK]
4	OK	1,13	*RMS* < 1,2; OK; NOTOK	OK
4	OK	1,31	*RMS* < 1,2; OK; NOTOK	NOTOK

5. Conclusion

This paper describes a method to prepare platform producibility assessments supporting set-based concurrent engineering. An aerospace sub-system in a welding assembly is provided to illustrate the approach. Two producibility aspects are studied – tool accessibility and assembly robustness.

To accomplish increased process efficiency in platform development, the integration between design and manufacturing must be improved. The use of an integrated platform supports the manufacturing providence needed to prepare producibility assessments across a design space. The assessment process blocks provided in this paper can be prepared in parallel and be arranged to find producible design alternatives within the platform bandwidth. The order of the process blocks needs to conform with the input and output of the activities. However, the order of the process blocks may have an impact on the size of the design space. This is a matter of future work.

The improved integration of manufacturing in platform development may facilitate early model-based producibility assessments of platform concepts. By using the suggested assessment process blocks in making producibility assessments of platform concepts the need for late design modifications and costly physical prototyping and testing can be reduced.

Acknowledgements

This work was carried out at the Wingquist Laboratory VINN Excellence Centre within the Area of Advance Production at Chalmers University of Technology in Gothenburg, Sweden. It has received support from the Swedish Governmental Agency of Innovation Systems (VINNOVA). This support is gratefully acknowledged.

References

[1] J. R. Jiao, T. W. Simpson and Z. Siddique, Product Family Design and Platform-Based Product Development: A State-of-the-Art Review, *Journal of Intelligent Manufacturing*, Vol. 18, 2007, pp. 5-29.
[2] S. M. Ferguson, A. T. Olewnik and P. Cormier, A Review of Mass Customization across Marketing, Engineering and Distribution Domains toward Development of a Process Framework, *Research in Engineering Design*, Vol. 25, 2013, pp. 11-30.
[3] J. Landahl, C. Levandowski, H. Johannesson, R. Söderberg, K. Wärmefjord, J. S. Carlson, J. Kressin, O. Isaksson and J. Vallhagen, Using Product and Manufacturing System Platforms to Generate Producible Product Variants. In: *6th CIRP Conference on Assembly Technologies and Systems (CATS)*, Gothenburg, May 16-18, 2016.
[4] M. H. Meyer and A. Lehnerd, *The Power of Product Platforms: Building Value and Cost Leadership*. New York, Free Press, 1997.
[5] J. Landahl, D. Bergsjö and H. Johannesson, Future Alternatives for Automotive Configuration Management, *Procedia Computer Science*, vol. 28, 103-110, 2014.
[6] C. Levandowski, *Platform Lifecycle Support Using Set-Based Concurrent Engineering*. Dissertation, Chalmers University of Technology, Gothenburg, Sweden, 2014.
[7] A. Alblas and H. Wortmann, The Need for Function Platforms in Engineer-to-Order Industries. In: *17th International Conference on Engineering Design, ICED 09*, Palo Alto, CA, USA, August 24-27, 2009.
[8] C. Levandowski, D. Raudberget and H. Johannesson, Set-Based Concurrent Engineering for Early Phases in Platform Development. In: J. Cha et al. (eds.) *The 21st ISPE International Conference on Concurrent Engineering - CE2014*, Beijing, IOS PRess, Amsterdam, 2014, pp. 564-576.
[9] J. Vallhagen, J. Madrid, R. Söderberg and K. Wärmefjord, An Approach for Producibility and DFM-Methodology in Aerospace Engine Component Development, *Procedia CIRP*, Vol. 11, 2013, 151-156.
[10] K. Wärmefjord, R. Söderberg and L. Lindkvist, Form Division for Welded Aero Components in Platform-Based Development, *Journal of Aerospace Engineering*, Vol. 28, 2014.
[11] M. T. Michaelis, *Co-Development of Product and Manufacturing Systems Using Integrated Platform Models*. PhD thesis, Chalmers University of Technology, Gothenburg, Sweden, 2013.
[12] Y. Koren, U. Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy and H. Van Brussel, Reconfigurable Manufacturing Systems, *CIRP Annals - Manufacturing Technology*, Vol. 48, 1999, pp. 527-540.
[13] A. Claesson, *A Configurable Component Framework Supporting Platform-Based Product Development*. PhD thesis, Chalmers University of Technology, Gothenburg, 2006.
[14] P. Schachinger and H. L. Johannesson, Computer Modelling of Design Specifications, *Journal of engineering design*, Vol. 11, 2000, pp. 317-329.
[15] S. C. Wheelwright and K. B. Clark, *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality*, Simon and Schuster, 1992.
[16] D. K. Sobek, A. C. Ward and J. K. Liker, Toyota's Principles of Set-Based Concurrent Engineering: *Sloan Management Review*, Vol. 40, 1999, pp. 67-84.
[17] C. E. Levandowski, D. Corin-Stig, D. Bergsjö, A. Forslund, U. Högman, R. Söderberg and H. Johannesson, An Integrated Approach to Technology Platform and Product Platform Development: *Concurrent Engineering: Research and Applications (CERA)*, Vol. 21, 2012, pp. 65-83.