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A framework for producibility and design for manufacturing requirements in a system engineering context

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Abstract

Aircraft engine technology has evolved and matured over a 70 year period under a continous pressure to become more sustainable, fuel efficient, noise efficient, etc. while ensuring robustness and cost efficiency in production and product operation through life. This paper addresses how current challenges, trends and practices enable the introduction of competitive production and through life operation support into new aircraft engine products. Specifically, the area of structural jet engine sub-structures and components is addressed, where product optimization is dominated by weigth optimization, but also characterised by increased expectations of functionality. As a means, novel manufacturing processes are introduced, and one means is to adopt a so called fabrication approach, where the component is build based on assemlying sub-components with better controlled properties into a component using various joining technologies such as welding. The paper presents a framework based on tigther refining a *systems engineering* and *requirements engineering* approach that, combined with a *set-based engineering* approach, allow for building of re-useable and adaptable engineering methods. Through systematically building this framework, and making use of state of the art modeling and simulation technologies, the introduction of the novel technologies necessarily to increase the engine sub-system performance can be realized without compromizing risk and cost. The paper displays by example some of the challenges that successfully have been addressed, and also some remaining that currently drive development of new practises, methods and tools. In conclusion, a more integrated framework to tie a systems engineering approach with the use of advanced modeling and simulation technologies in a reuseable manner, is a way to balance between product performance and producibility. Still the area is undergoing intence development and challenges for research, development and practice still remain.

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Keywords: Design For Manufacturing; Producibility; Systems Engineering; Set-based Engineering; Platforms; Aerospace Engine Components; Fabrication

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1. Introduction

Performance and reliability of modern jet engines have improved immensely since the first installation some 70 years ago. Such improvement have been the result of advances in many areas, including materials technologies and manufacturing technologies, but also in systems design and engineering design methods and practices. Over the last decades, engine manufacturers increasingly offer functionality and availability through advanced business models, which directly ties the engines in-service behavior to the manufacturer. The jet engine becomes more optimized and integrated as a system, and the through life responsibility for manufactures opens up the in-service behavior to be a key design issue.

In search for even higher performance, new engine architectures are being developed and demonstrated, such as *Geared Turbo Fans* (GTF), *Ultra High Bypass Ratio* (UHBR) and *Open Rotor* [1].

On engine component and sub-system level, weight optimization and cost effectiveness drive development of new materials and manufacturing technologies, and the integral function of the engine system require the sub systems to be designed tightly together with the engine architectural design. To exploit the attractive features of novel manufacturing approaches, such as additive manufacturing techniques and composite designs – their impact on both the engine system

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and the through life behavior must be well known already in the design stages. High performance materials and weight optimized designs are enabled through equivalent advances in inspection and repair technologies. Optimized components typically come with tougher requirements on tolerance design and carefully designed margins, and the overall system performance becomes increasingly dependent on detailed definitions on sub system and component level. Several large scale aircraft and engine development programs has suffered from late discovery of limitations on detailed level, where design and manufacturing solutions selected at an early stage cannot match the overall system behavior. The solutions have not been able to meet the producibility requirements.

Design for Manufacturing (DFM), [2, 3, 4] addresses the dependencies between the engineering design and the production capabilities, yet – does not address the relation to the engine system and performance.

Systems Engineering (SE), on the other hand, addresses the overall function of the engine as a system and how the integrated engine can be defined as a unit. To an increasing extend, advances in systems engineering has encompassed the life cycle aspects into integrated models, yet – there are still weak couplings to component engineering design and manufacturing process design.

Producibility can be seen as a term for a robust development of products that meet overall systems requirement with both cost efficient and functional performance solutions. Later research has given attention to design and engineering aspects of producibility [5, 6, 7, 8, 9] within aerospace applications.

The knowledge gap addressed in this paper is the ability to account for manufacturing process capabilities and how these affect overall engine performance already in the design phases. In a recent study, this gap was identified and a survey of candidate methods for linking producibility and production process aspects into design [27].

A main challenge for introducing through life- and manufacturing aspects into early design phases is the quality of data available. Resolution and robustness of design loads are seldom stable and the knowledge about operative conditions are limited to scenarios and high level specifications (or experience from pervious designs).

The *aim of this paper is to present a framework that enables design for manufacturing in a systems engineering context*. The accompanying Research Question (RQ) becomes *how to support such multi-disciplinary framework and include producibility aspects into the design work?*

In the paper, the current practices are briefly reviewed, and their limitations highlighted. The following section presents a framework for robust development, followed by a discussion and conclusion section. The arguments are supported by real world examples.

2. Engineering practices in change

2.1. Engineering for producibility

Current design practice is changing. The first aircraft engines were designed without the power of computers using hand calculations, tables, graphics and careful experimentation. Today, computers are the backbone for virtual engineering, essentially supporting any engineering activity. Improvements in computer aids are evolving radically, and from being a replacement or powerful aid to "know" engineering methods, we can now use computer tools to design in new ways – governing the development of new work practices.

Producibility has always been an issue, and we now use computer tools to model and simulate also the production process. Consequently there is a push to reduce the number physical development tests, and introduce virtual tests. Such tests allow more exploration of variants, but are always based on assumptions and imprecision's in the virtual modeling and simulation techniques. The need to undertake physical tests to validate virtual technologies consequently increases.

Although virtual tools exist and are in use, these are typically used within their expert domain. Such tools are seldom designed to support the design and assessment from an integral – or systems – point of view. There is a need to make efficient use of domain tools in combination with experiences and continuous improvement. Ability to combine "experience management" with modern computer tools capabilities is a competitive advantage if well established.

As an example, the performance requirements require adoption of more advanced materials and sophisticated manufacturing technologies. Using more advanced manufacturing technologies is often challenged by robustness, and may impact producibility in a negative sense.

This results in a situation in which there is a lack of experience and knowledge about the *ideal* process application and its conditions. This is the paradox of novel technologies; it enables a new advanced product design, but the manufacturing and production system performance may be affected negatively, at least at the very start and it takes a lot of work to improve and optimize the production performance. This is illustrated in Figure 1, where the "S"-curve is used to illustrate the situation when several new technologies are introduced at the same time.

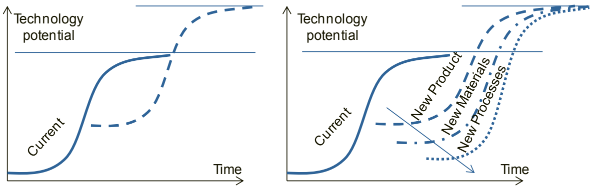

Fig. 1. Left: The current technology will reach the maximum potential and need to jump to a new S-curve with higher potential. However at the time of shifting the new technology may need some time to close the gap. Right: The more shift in technologies the greater combination of risks and time needed to mature each technology and utilize its full potential. However, the total positive effect may be larger at the end.

As the evolution in product performance increases, the production system and process to realize the product technology is also affected. The dependencies between the product and production system performance becomes increasingly tangled. As an example, the introduction of component assembly through fabrication enables more optimal product properties, whereas this introduces more production steps. Complex casting is replaced by an advanced assembly process. The adaption of the "knowledge system" of how to build castings have emerged from years of experiences, whereas a new manufacturing approach by definition need a new set of knowledge capabilities.

Already today, and increasingly tomorrow, there is an increasing need to co-design the manufacturing process with the product design process. Despite the adoption of advanced virtual modeling and simulation technologies, there is a significant gap between understanding the overall product performance and behavior in situations where the governing behavior is determined by production and manufacturing process capabilities.

3. Introducing a framework for robust development

In this section we present a practical framework consisting of several parallel principles and mechanisms that together give a business impact. The framework is being developed and introduced at GKN Engine Systems, as an important means to enable robust development. This framework has a number of key features that constitute the base for robust development, namely:

- The use of platforms
- The use of virtual methods
- The introduction of through life engineering
- Set based and Systems Engineering

In Figure 2, the set based engineering value streams [10] are illustrated. The *Knowledge Value Stream* (KVS) represent the systematic building of knowledge over time; whereas the *Product Value Stream* (PVS) represent the process to make efficient use of available knowledge (from KVS) once a target product application (most often technologies and components for new engine development) has been initiated.

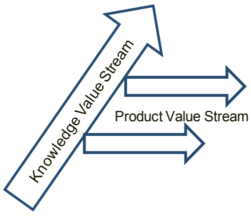

Fig. 2. Knowledge value stream vs. product value stream (adapted from [10])

3.1. The use of platforms

Platform engineering is well known on OEM system level, in particular in B2C markets where product volumes are high. In aerospace, platforms have also been driven by maximizing re-use of valid engineering solutions. For sub-systems however, platforms have not been extensively adopted.

At GKN Aerospace Engine Systems platforms have been introduced to enable re-use of technologies, product design solutions and production system solutions. To guide the product design and production set-up for a specific type of components, a production platform has been developed. It includes a standard *Bill of Material* (BOM) and standard *Bill of Process* (BOP) for the preferred solutions. Together with generic guidelines and specific requirements and constraints, these provide the targeted production environment and its capabilities. The production process is based on best practice and the strategic production system information. As more experience is gained, the validity and experience are explicitly stated through updates of the platform definition. One major role of the production platform definition is as a mean for communication and decision making. For the context of this paper, the production platform contains both a concise representation of the targeted production system and a key source for requirements to be used in design phases.

In parallel, the design and development organization defines the product platform in an equivalent way to capture and express the preferred product configurations and their behavior for specialization products.

Finally, the development and maturation of the technology platform follow similar logics, and capture and represent maturity of core technologies used in both products and processes. The introduction of the three views of platforms is described in [11].

Meanwhile, the engineering design systems are tailored to support the use of platform information, that is – to allow re-use of the knowledge gained from technology development and previous programs [12].

The first experiences of the platform based approach reveal benefits on several levels. First as a source for requirements and contextual information, that has been difficult to assemble, secondly as an important means for communication between different organizational functions within the company. These experiences are promising, yet – there is still need to improve the use of the "new" source of information in development situations. Thus, the conclusion is that there are a good potential for improving communication and establish a single source of information.

The main effect of the "platform" feature of the framework is that it provides a way to obtain a shared understanding and unique reference.

3.2. The use of virtual methods

Virtual methods, including modeling and simulations, are used to enable decision making throughout development. Previously, virtual modeling methods have been introduced for structural mechanics, aerothermodynamics and fluid mechanics to design the product. More recently, virtual methods have been introduced to also understand, analyze and even optimize manufacturing processes. Since simulations can be made in early phases, such studies are used to establish manufacturing requirements and assess consequences of various design variants onto manufacturability and vice versa.

Here, the deliberate strive to use virtual methods have already impacted best practices. The use of virtual methods in establishing requirements is one example.

Somewhat simplified, it can be argued that the ability to simulate product behavior is already in use. Simulations of various manufacturing aspects are also being successfully introduced. An example from GKN of a process simulation is development of welding simulation and its integration into design systems [13]. The simulation of welding is in regular use for both design and production activities today [13].

This tool provides the ability to evaluate the effect of welding on distortions and induced stresses in the product due to the actual welding process, already during design. In combination with experimental tests, such simulations are used to capture and implement knowledge and experience into dedicated simulation tools.

Design for producibility is being reported in [14] as a collective label to tailor computer based modeling and simulation support in product development. Another example is introduction of geometrical robustness simulation, based on Robust Design & Tolerancing (RD&T) applications. RD&T is a software for variation simulation and robustness evaluation [16]. This application area supports the whole life-cycle from concept development, to detailed design, inspection planning, data analysis and process control, and root cause analysis [17]. Also non-rigid variation simulation is supported [18]. The key benefits from a manufacturing perspective are that this methodology enables the implementation of a clear strategy and principles for a robust design [20, 21]. The purpose is to make each step in the process chain less sensitive to variation which improves the conditions for e.g. the following assembly processes and sub-assemblies. Since a few years, there is also research looking into the combinatory effect on geometrical variation and weld simulation for assemblies [17].

A third example is *Discrete Event Simulation* (DES) which, on a production system level, is used to evaluate different layouts, logistics and production control solutions to see the effect on materials and production flows, resource utilization, etc. This is a powerful tool to verify how the requirements and targets are met for cost and time related production metrics. The accuracy of the simulation model and the results are dependent on e.g. capability/yield and other variations from each process step. Thus, it is quite important to understand and predict this to achieve a good correlation between the real world/output and the virtual world.

There are simulation methods for other processes as well e.g. for sheet metal forming and machining to evaluate the process parameters and the resulting product properties. From a holistic perspective, especially in producibility and manufacturing performance perspective, there is interesting opportunities and benefits from combining simulation of the different steps to better understand the total system [5].

It may be argued that the bottleneck of achieving a robust product and process solution now is the integrative decision making. Simulation of multi-aspects are being researched [15] and there is a significant challenge with "hidden factors" that are simply not captured and represented in the simulation models which has been identified by *National Defense Industry Association* (NDIA) [5].

The main effect of the "virtual methods" feature of the framework is that it enables multiple studies and variation in experimentation. Such variation is at best expensive in the physical domain. A second feature is the ability to use virtual methods to create, or at least validate, early phase design requirements.

3.3. The introduction of through life engineering

As service based business models enforces manufacturers to ensure functionality and availability in service the importance of careful design decisions taking through life aspects into account increases. In particular since the introduction of new – high performance materials may require new and advanced inspection techniques, repair technologies etc.

As one example, there are high level expectations on availability and turn-around time for maintenance. For sub systems and components design this mean that lead time for assembly – and disassembly, of components on the engine becomes important. Such requirements have been introduced into the engineering design systems, and there are now methods to include geometrical access and the design of flanges, fasteners etc. are being design for maintenance.

Other examples that have become apparent are the ability to detect and inspect products in service, something that increasingly become decisive for selecting the design concept, and consequently need to be accounted for already in the conceptual design.

3.4. Set-based and systems engineering

Set-based concurrent engineering [24, 25] has been introduced as an important means to identify limits and restrains, and exclude non-viable and non-sustainable solutions as opposed to selecting and refining concepts. The identification and use of trade-curves is appealing from a communication point of view, and the approach promotes sound principles that allow progression and maturation through the innovation work.

Deploying set based engineering presumes evaluation of several "points" in the design space. This is done either through evaluation of a certain solution for a range of conditions, or evaluation of several solution variants for different situations. The amount of evaluation points (sets) can be enabled through simulations.

As an example, GKN has introduced engineering automation techniques to enable both generation and evaluation of design alternatives during development. Early attempts showed promising result for how to integrate further restraints from manufacturing and in service support together with "traditional" evaluation of functions [26].

The automation of engineering design and engineering simulation activities is a necessity to allow exploration of an entire set of solutions and conditions and there is consequently an appealing approach that combines simulation technologies with development principles.

The main effect of the "set based" feature of the framework is that it provides a robust approach to design and increase the adaptability to changes.

4. Discussion

This paper addresses the challenges and complexity due to the introduction of new technology and concepts for light weight aerospace engine components. The current DFM techniques are challenged by this complexity and need for specialized simulations. To reach the objective – a well-balanced product both from a product performance perspective and a product realization (production) perspective – there is a need to evolve practices for DFM as well as the overall engineering practices.

To answer to the research question a four-bullet framework has been presented, with the purpose to meet the upcoming situation for engineering. This framework comprises of four principle areas that together form a consistent approach in search for next best practice. Early experiences from deploying these four bullets have been presented to explain how these fit together, which also is illustrated in Figure 3. The use of platforms (1) set the infrastructure to capture and re-using information and experiences in an organized way. The use of simulation (2) allows decision making for most aspects necessary throughout development. The experiences and new knowledge gained from the simulations should also be feed back into the knowledge value stream to improve the platforms and future products. Special emphasis to capture through life engineering characteristics (3) is needed due to the importance of in service support and refinement. Altogether there is a need to bring systems and set based engineering closer to engineering development and as a means to turn platform development into applicable business applications (4).

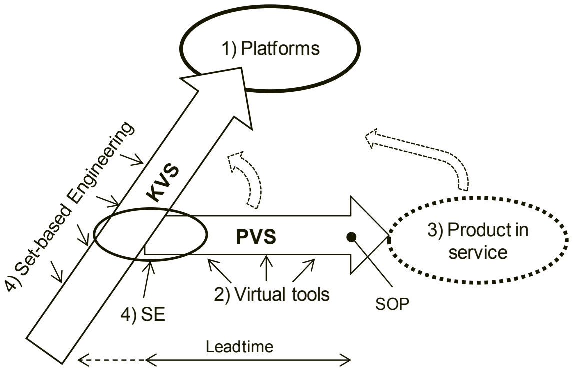

Fig. 3. The framework with its principles.

Experiences from introduction of these four principles at GKN reveal effects on several levels. The most apparent positive effect is the organization of information as a means of communication between various stakeholders in the company. The introduction of a production platform explain in a concise way the preferred and allowable industrialization capabilities, and is a source for development in design teams and production teams alike.

5. Conclusions

It has been argued that the dependency between manufacturing and production capabilities and the overall system performance become increasingly dependent and that development practices need to evolve accordingly,

The framework presented shows a coordinated effort to address the producibility aspects. Especially in situations where new materials, product and manufacturing technologies are introduced at the same time and producibility and manufacturing requirements need to be fulfilled. Computer tools have matured and are becoming more capable of simulating behavior of products and processes. The limitation is in mastering the multi-faceted situation with tools and methods tailored and specialized for different purposes.

The most important aspect is the organized way to facilitate a transition in practices, through making use of simulation capabilities and through life data to feed the knowledge value stream bringing the set-based and systems engineering work closer to engineering teams and their practices. Future wise, the presented work highlight areas in which further technological and methodological advances can be expected.

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References

[1] SAGE - Sustainable and Green Engines http://www.cleansky.eu/content/page/sage-sustainable-and-green-engines.

[2] J. Bralla, Design For Manufacturability: Handbook, 2nd ed., McGraw-Hill Handbooks, 2004.

[3] D. T. Koening, Manufacturing engieering: principles for optimization, 2nd ed., Taylor & Francis, 1994.

[4] G. Chryssolouri, Manufacturing systems: theory and practice, 2nd ed., New York: Springer Science + Business Media, Inc., 2006.

[5] D. A. Sanders, Modeling & Simulation Investment Needs for Producible Designs and Affordable Manufacturing. systems Engineering Implications, NIDA JCSEM M&S. Sub-Committee , USA, February 2010.

[6] D. Hoopes, Improving producibility in aerospace engine manufacturing : process automation vs. process reengineering, Leaders for Manufacturing Program Publisher. Massachusetts Institute of Technology, Massachusetts, 2008.

[7] J. R. Hadley and D. J. McCarthy, Producibility and confidence indices during defense acquisition, in *NDIA Ground Vehicle Systems Engineering and Technology Symposium*, Michigan, August 2011.

[8] A. Sanders, Manufacturing Maturity in S&T an Industry Perspective, The annual Defens Manufacturing Conference (DMC), Orlando, 2009.

[9] S. Ramaswamy, A Survey of DFM Method, Department of Mechanical and Aerospace Engineering, Arizona State University, 1998.

[10] Kennedy, M., Harmon, K., Minnock, E., Ready, Set, Dominate: Implement Toyota's Set-Based Learning for Developing Products and Nobody Can Catch You, The Oaklea Press, 2008.

[11] Högman, U. Processes and Platforms Aligned with Technology Development, PhD thesis, Department of Product and Production Development, Chalmers, ISBN 978-91-7385-542-6.

[12] Andersson, P. Support for Re-use of Manufacturing Experience in Product Development - From An Aerospace Perspective, PhD Thesis, Luleå university of technology, 2011.

[13] H. Runnemalm, H. Tersing and O. Isaksson, Virtual manufacturing of light weight aero engine components, in International Symposium on Air Breathing Engines, Montreal, Canada, 2009.

[14] F. Elgh, Computer-Supported Design for Producibility - Principles and Models for System Realisation and Utilisation, PhD thesis, Department of Product and Production Development, Chalmers, ISBN 978-91-7291-975-4.

[15] Forslund, A., Levandowski, C., Lööf, J., Söderberg, R. Lifecycle Robustness Optimization of Turbine Components Using Simulation Platforms, in Proceedings of the 28th Congress of the International Council of the Aeronautical Sciences, ICAS 2012.

[16] Söderberg, R. and Lindkvist, L., Computer Aided Assembly Robustness Evaluation. Journal of Engineering Design, 1999. 10(2): p. 165-181.

[17] Söderberg, R., Lindkvist, L. and Carlson, J., Virtual Geometry Assurance for Effective Product Realization. 2006. Göteborg, Sweden: 1st Nordic Conference on Product Lifecycle Management – NordPLM'06.

[18] Wärmefjord, K., R. Söderberg, and L. Lindkvist. Tolerance simulation of compliant sheet metal assemblies using automatic node-based contact detection. in Proceedings of IMECE2008. 2008. Boston, USA.

[19] Pahkamaa, A., Wärmefjord, K., Karlsson, L., Söderberg, R., Goldak, J., Combining Variation Simulation With Welding Simulation for Prediction of Deformation and Variation of a Final Assembly. Journal of Computing and Information Science in Engineering, 2012. 12(2): p. 021002-021007.

[20] J. Vallhagen, J. Lööf, R. Söderberg, K. Wärmefjord, Robustness in aerospace components manufacturing and fabrication - a case study. International Symposium on Air Breathing Engines, Göteborg, Sweden, 2011.

[21] Lööf, J., Söderberg, R. & Lindkvist, L. Optimizing Locator Position to Maximize Robustness in Critical Product Dimensions. Proceedings of the ASME IDETC/CIE, 2009, San Diego, California, USA.

[22] Lockett, H., Johnson, M., Evans, S. Bastl, M., Product Service Systems and supply chain network relationships: an explorative case study, Journal of Manufacturing Technology Management, Vol 22, No 3, 2011, pp. 293-313.

[23] Isaksson, O., Kossmann, M., Bertoni, M, Eres, H, Monceaux, A., Bertoni, A., Wiseall, S., Zhang, X., "Value-Driven Design - A methodology to Link Expectations to Technical Requirements in the Extended Enterprise", Incose seminar, Philladelphia, 2013.

[24] A. P. Sage and W. B. Rouse, Handbook of System Engineering and Management, 2nd ed., New Jersey: John Wiley & Sons, Inc., 2009.

[24] D. K. Sobek, A. C. Ward and J. K. Liker, "Toyota´s Principles of Set-Based Concurrent Engineering," vol. 2, no. 40, Winter 1999.

[25] Raudberget, D., Industrial experiences of set-based concurrent engineering, licentiate thesis, scool of engineering, jönköping university, ISSN 1652-9243, 2012.

[26] Boart, P, Isaksson, O., Enabling variation of manufacturing process parameters in early stages of product development, in Proceedings from ASME/IMECE 2006, paper IMECE2006-14459.

[27] J. Vallhagen, J. Madrid, R.Söderberg, K. Wärmefjord, An approach for producibility and DFM-methodology in aerospace engine component development, Proceedings of the 2nd international through-life engineering services conference, Cranfield, UK, 2013.