ASSESSING SYSTEM MATURITY OF INTERACTING PRODUCT AND MANUFACTURING ALTERNATIVES BEFORE EARLY TECHNOLOGY COMMITMENT

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ABSTRACT

This paper presents a new way to support early assessment of interacting product and manufacturing technologies based on system maturity. This approach is illustrated by an example from the aerospace industry, where alternative technologies are introduced in an existing product and manufacturing systems platform. By assessing the system maturity of interacting technologies, alternative solutions can be eliminated before early technology commitment. This is beneficial for 1) clarifying the company's status regarding capability and maturity, 2) eliminating immature technologies within a certain capability bandwidth, and 3) prioritizing advanced technology development initiatives with respect to the risk of implementing a manufacturing technology to interact with a product technology. It may also enable reduction in design rework and manufacturing rework that comes with failed maturity matching of product systems and manufacturing systems, thus possible reduction in lead-time and cost could be met.

Key words: Set-Based Concurrent Engineering, Integrated Product and Manufacturing Systems Platform, Technology Readiness, System Maturity

INTRODUCTION

The market of products is ever changing. New technologies replace old ones and product functionality is regularly added to meet the needs and requirements of distinctive customers. Early planning initiatives of a product include conceptual design freedom yet uncertainties. Despite the uncertainties, early decision of the product design is based on gut feeling and experience, since predicting future changes in early phases of development is beyond reasonable expectations. During the lead-time of developing a product, from conceptual phases to production ramp-up, the market will change, which may require regular, and costly, adjustments to an early and fixed product design. Yet, it is not solely the market that affects the cost and lead-time of the product. The influence of how manufacturing affects the product design is seldom a part of the design process until a geometry model, or an embodiment, of the product is available (Bruch and Johansson, 2011), hence late in the development process. When the product design is decided upon, based on requirements and means of performance, it will be evaluated to fit a suitable manufacturing technology. The manufacturing technology is then picked based on, partly the company's capability and partly previous experiences of manufacture similar products. If the product design does not fit a suitable manufacturing technology, due to predicaments such as high cost or low maturity of the manufacturing technology, its capability needs to be advanced or a less suitable manufacturing technology may be applied while unwanted changes to the product design needs be considered to fit a specific manufacturing technology. This is referred to as point-based design (Ward et al., 1995), and is characterized by an early commitment to a design that is carried into subsequent stages of development. Converse to point-based design, a design methodology which offers the ability to be responsive to changes, is Set-Based Concurrent Engineering (SBCE) (Ward et al., 1995). SBCE is a highly efficient development methodology, considered to be a vital part of the Lean Product Development System. SBCE is characterized by working with multiple solutions simultaneously and systematically explore trade-offs between different alternatives. An additional approach for efficient product planning and development is to adopt a platform strategy. A platform can be used as a means to reuse both design and manufacturing knowledge.

When an organization move from point-based design to SBCE, the number of design alternatives will increase. To avoid spending an excessive amount of resources on unfeasible alternatives, the evaluation and elimination of these unfeasible alternatives is essential.

Scope of Paper

In this paper we propose a new way to support early assessments of product and manufacturing technologies based on maturity. The systems are modeled following the Configurable Component framework (Claesson, 2006).

The objective is to present the assessment and comparison of interacting systems based on maturity levels of interacting technology elements. The technology elements are represented in an integrated product and manufacturing system platform with elements from both product and manufacturing domain. In this integrated platform, interactions between elements are defined. To eliminate unfeasible solutions, there is a need for preliminary information from downstream processes, such as manufacturing, to assess the evolving platform.

The state of the art is limited to the intersection of object-oriented platform development methodology, SBCE and system maturity. An illustrative example from the aerospace industry is formed to show how the introduction of alternative welding technologies will affect the existing integrated product and manufacturing system platform.

Platform Theory

Platform-based design is an approach that has received positive attention the last decades as a way to save costs associated with manufacturing, thus economies of scale in production. Initially, the goal was to increase the reuse of existing subsystems and components within a product family or between product generations by creating a common structure that is used as the basis of derivative products. The definition of platforms has evolved to incorporate other assets beyond physical parts, such as system objects with knowledge of design and manufacturing.

A Platform Model based on Systems

The Configurable Component (CC) concept is an object-oriented approach to describe system platforms. It contains reusable elements, which are scalable as well as structurally configurable . They can be used to support development of product platforms as well as manufacturing system platforms (Michaelis et al., 2014) and, to some extent, technology platforms (Levandowski et al., 2013).

The objective of the CC concept is to manage both complexity and variability (Landahl et al., 2014). The concept is based on principles of systems theory and design theory.

Each CC element holds a system family, containing information about the system solution itself, the means to compose system variants and its underlying requirements and motivations, i.e. its Design Rationale (DR). The DR is based on Enhanced Function-Means (E-FM) modeling deliberated by Schachinger and Johannesson (2000). E-FM modeling includes descriptions of interactions between Functional Requirements (FRs), Design Solutions (DSs) and Constraints (Cs), as illustrated in Figure 1.

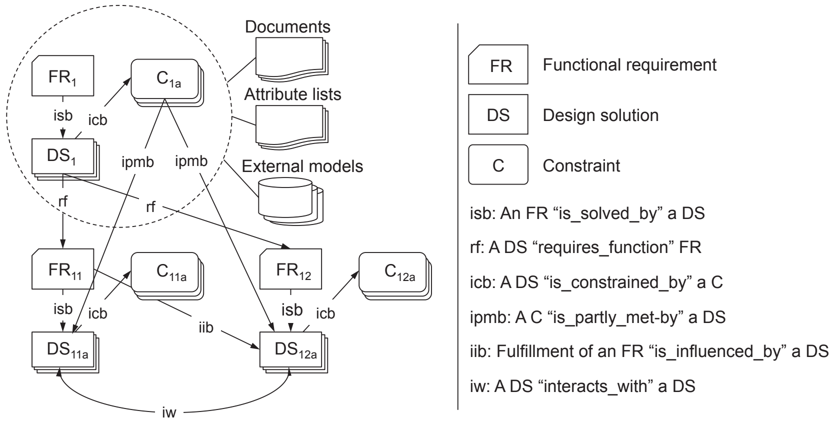


Figure 1: The enhanced function-means tree describing Functional Requirements, Design solutions and Constraints (as drawn in Michaelis (2013), adapted from Johannesson and Claesson (2005))

A CC element interacts with other CC elements through the Control Interface (CI), Composition Set (CS), Interface (IF), or Interaction (IA) entity. A CC element with its Design Rationale is illustrated in Figure 2.

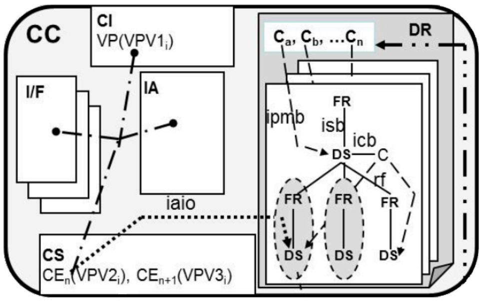


Figure 2: A CC element with its Design Rationale (DR) and entities; Control Interface (CI), Composition Set (CS), Interface (IF) and Interaction (IA).

Bandwidth and Reusability

A platform is prepared to fulfill a range of requirements. This range can be referred to as the platform's bandwidth (Berglund and Claesson, 2005). Both scalable bandwidths as well as structural bandwidths can be constructed. The concept of bandwidth is used to define the platform's initial limitation of design space. An illustration of the scalable bandwidth is the wide range of sizes of wheel rims used for a vehicle. Likewise, an illustration of the structural bandwidth is the number of wheels used for a vehicle. With the ability to incorporate both types of bandwidths, the platform is prepared to hold a vast amount of both pre-embodiment representations and system family representations that can be configured to form product variants. The CC concept is developed to represent these different solutions, which also can be reused in various applications. Reuse of CCs is applicable for development of platforms for existing or new settings, elaborating the design space in engineer-to-order settings, and systematic configuration of quality assured variants within the platform bandwidth (Johannesson, 2014).

Set-Based Concurrent Engineering for Integrated Systems Platforms

Set-Based Concurrent Engineering, (SBCE) (Ward et al., 1995), is a development methodology considered a vital part of the Lean Product Development System. It is interpreted differently by different authors, and this paper follows the principles given in (Sobek et al., 1999): 1) *Map the design space*, 2) *Integrate by intersection*, and 3) *Establish feasibility before commitment*.

Briefly, the concept of SBCE is characterized by working with a set of solutions, a palette of different solutions to a specific function or problem. These sets are systematically explored to learn about the trade-offs between different alternatives. SBCE considers sets of design alternatives rather than a specific design, and in that aspect it suits platform system development well. The term set-based is opposed to the term point-based (Ward et al., 1995), describing the traditional development methodology. Point-based design is characterized by an early selection and approval of one best design, thus a single point in the design space. This initial design is then refined, re-worked and sequentially modified until an acceptable solution is found. One example of a point-based process is the case of product engineers delivering one flawless design to production for assessment of producibility. Such a case seldom goes through the assessment without design changes.

Previous authors have suggested SBCE for platform preparation while adopting the Configurable Component system description approach (Levandowski et al., 2014a, Levandowski et al., 2014b) with its concept of bandwidth and use of multiple Design Solutions. Both are compatible with the principles of SBCE as seen in Table 1.

The first principle, *Map the design space*, incorporates developing sets of design alternatives in each technical discipline, such as design, manufacturing or both. Specific designs are not considered alone; instead the disciplines share all design alternatives with the other disciplines. For platforms adhering to the CC concept, it refers to multiple DSs being generated for each FR.

The second principle, *Integrate by intersection*, focuses on reducing the number of solutions in the sets. This is balanced by the desire to keep the design space unrestricted until sufficient information is acquired to enable design commitments. For platforms there are several mechanisms suggested to fulfill this principle. The bandwidth is suggested as a means to eliminate solutions that fall outside the permitted range (Levandowski et al., 2014b). As a means to further limit the design space, constraints can be applied in the form of for example geometrical properties, weight or cost. To further eliminate unfeasible solutions, a complementary way to the concept of bandwidth and constraint is trade-off curves that enable visualization of conflicting requirements, such as functional requirements and performance properties. Also architectural options can be defined to identify a number of discrete architectures where the members of the individual design solution sets are compatible. To further reduce the number of alternatives, functional couplings within the product platform can be identified and quantified in order to eliminate solutions that have complex couplings (Raudberget et al., 2014).

Table 1: The principles of SBCE.

Overall principles	Sub-principles
1) *Map the design space*	- Define feasible regions - Explore trade-offs by designing multiple alternatives - Communicate sets of possibilities
2) *Integrate by intersection*	- Look for intersections of feasible sets - Impose minimum constraint - Seek conceptual robustness
3) *Establish feasibility before commitment*	- Narrow sets gradually while increasing detail - Stay within sets once committed - Control by managing uncertainty at process gates

For the present research, the process of integrating manufacturing information is supported by the third principle, *Establish feasibility before commitment*. By including manufacturing information, it will be possible to eliminate solutions that are not feasible or fall outside the required bandwidth.

Elimination of Unfeasible Solutions in the Early Phases

SBCE and the CC platform can be used to address abstract and incomplete representations (pre-embodiment) for emerging parts of the system on equal terms as the exiting technology. This makes it possible to evaluate architectures of emerging technologies before they are mature. As the design evolves, the number of architectures and the set of solutions are gradually narrowed. By using the SBCE methodology for decision-making, solutions can be reduced. Instead of selecting the most promising designs, SBCE supports systematic elimination of unfeasible solutions. An industrial case study (Raudberget, 2010a) concluded that the SBCE decision process gives different results compared to the better-known Pugh method of controlled convergence. Another aspect is the efficiency of the SBCE decision process. Contrary to the selection of alternatives, the elimination of alternatives can be done confidently from incomplete information.

There are few methods for assessing solutions based on manufacturing information in early phases of development. The natural direction of information during development originates in upstream activities, through the scoping of the platform prerequisites in standardized process models such as the Stage-gate model (Cooper, 1985). Subsequent work is carried out through well defined development models such as Pahl (2007) and Ulrich and Eppinger (2012). Here, a variety of formal documents are produced that describe the products or platforms including for example requirements, drawings, assembly sequences, bill-of-materials arriving at a detailed definition of a product platform.

The management of specifications in SBCE is an important distinction from traditional development (Ward et al., 1995, Raudberget, 2010b). In SBCE, the individual requirements are not fixed numbers but rather a range of upper and lower limits representing the design space. This corresponds to the concept of bandwidth in the CC concept. In the process of eliminating platform members the bandwidth of a technology plays an important role for the decision to keep the technology in the solution set.

The Framework of System Maturity

In the work of maintaining a platform (Levandowski et al., 2014b), the system designer has to know which subsystems need to be developed to a higher level of maturity (Magnaye et al., 2010). Thus, a metric for system maturity can be useful.

Ever since mid 1990's, NASA have utilized the Technology Readiness Level (TRL) scale to assess maturity, or readiness, of technology elements (Mankins, 1995). This initial work by NASA had the main objective to define risks and costs corresponding to the development of advanced technologies. However, the TRL scale has some drawbacks. It is, for example, not considered a comprehensive framework for assessing maturity of interacting technologies or subsystems in an operational system (Mankins, 2002, Sauser et al., 2006). To improve the usefulness of the TRL scale, a link between product and manufacturing has been developed by the U.S. Department of Defense, DoD (2001), resulting in the Manufacturing Readiness Level (MRL). The MRL is a complementary maturity scale to the TRL scale, however it will not be a part of the presented study. Instead, we consider a technology as arbitrary for any domain, whether it adheres to product or manufacturing. The definition of the TRL scale is described in Table 2.

Table 2: Technology Readiness Level scale definition (DoD, 2001)

TRL	Definition
9	Actual system proven through successful mission operations
8	Actual system completed and qualified through test and demonstration
7	System prototype demonstration in operational environment
6	System/subsystem model or prototype demonstration in relevant environment
5	Component and/or breadboard validation in relevant environment
4	Component and/or breadboard validation in laboratory environment
3	Analytical and experimental critical function and/or characteristic proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and reported

Integration Readiness Level (IRL)

The intention for TRL was never to measure the maturity of interacting elements (Sauser et al., 2006). Therefore, the Integration Readiness Level was developed to provide a framework for assessing the maturity of interacting technologies. One of the most promising aspects of the IRL is the support to uncover any mismatch of integrating technologies even though the TRLs of each technology may be high (Sauser et al., 2010). The definitions of the IRLs are given in Table 3.

Table 3: Integration Readiness Level scale definition (Sauser et al., 2010)

IRL	Definition
9	Integration is Mission Proven through successful mission operations
8	Actual integration completed and Mission Qualified through test and demonstration, in the system environment
7	The integration of technologies has been Verified and Validated and an acquisition/insertion decision can be made
6	The integrating technologies can Accept, Translate, and Structure Information for its intended application
5	There is sufficient Control between technologies necessary to establish, manage, and terminate the integration
4	There is sufficient detail in the Quality and Assurance of the integration between technologies
3	There is Compatibility (i.e. common language) between technologies to orderly and efficiently integrate and interact
2	There is some level of specificity to characterize the Interaction (i.e. ability to influence) between technologies through their interface
1	An Interface between technologies has been identified with sufficient detail to allow characterization of the relationship

Sauser et al. (2008) argue that the interpretation of the independent IRL levels may need clarification. However, a complementary checklist has been developed by Sauser et al. (2010) which claim to remove some of the subjectivity that exist in many maturity metrics. However, there are still doubts about the current way to assess the IRL, since there is no quantitative algorithm to make one single assessment.

System Readiness Level (SRL)

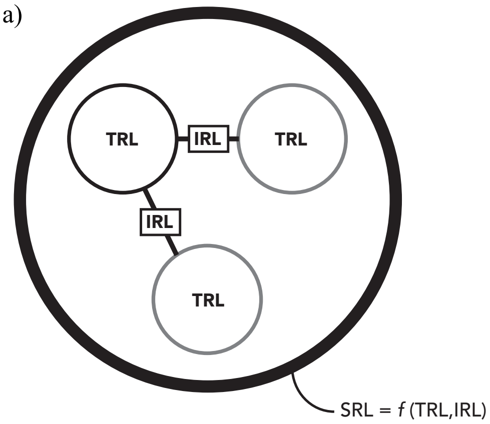
The System Readiness Level (SRL) scale is a framework based on independently assessed readiness of technologies, and the influence of integration between them. The framework could be used to estimate the maturity of a system under development by systematically evaluating alternative system solutions (Sauser et al., 2008). It can provide the system designer the ability to narrow sets of unfeasible solutions, which is a cornerstone in SBCE and valuable support for early phases of platform development (Levandowski et al., 2014b). What characterizes the SRL scale from the TRL scale is the interaction between technologies (IRL) and the strong link to acquisition phase. The definition of the SRLs is described in Table 4.

The framework of system maturity, and how to calculate the SRL value is shown concisely in Figure 3a) and 3b). The SRL is deliberated more in depth in e.g. Sauser et al. (2006), Sauser et al. (2008) and Sauser et al. (2010).

Table 4: System Readiness Level scale definition with corresponding acquisition phase (Sauser et al., 2008)

SRL	Acquisition Phase	Plan
0.90 to 1.00	Operations & Support	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total lifecycle
0.80 to 0.89	Production	Achieve operational capability that satisfies mission needs
0.60 to 0.79	System Development & Demonstration	Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility
0.40 to 0.59	Technology Development	Reduce technology risks and determine appropriate set of technologies to integrate into a full system
0.10 to 0.39	Concept Refinement	Refine initial concept; develop system/technology strategy

a)



b) $$[SRL]_{n\times 1} = \frac{\frac{[IRL]_{n\times n}}{9} \times \frac{[TRL]_{n\times 1}}{9}}{n}$$

Figure 3: a) Description of the framework of System Readiness Level (SRL), and b) the calculation of the SRL value (adapted from Sauser et al. (2008)).

RESULTS AND ILLUSTRATIVE CASE

To illustrate the approach we present a case from the aerospace industry. The case company is a jet engine component supplier that is responsible for mechanical design and manufacturing of static parts for jet engines. The studied product, Turbine Rear Structure (TRS), is located at the rear of a jet engine, which is illustrated in Figure 4. Each TRS is manufactured at a yearly volume of approximately 400 units and is customized for different customer's requirements.

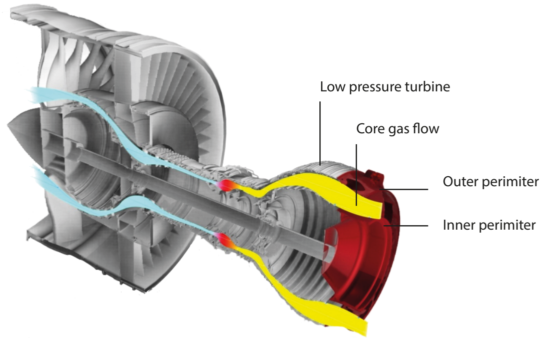


Figure 4: A section view of a turbo-fan engine. The TRS is highlighted in red (Levandowski et al., 2014b).

Illustrative Case

The illustrative case is based on technology integration between a product system and four different welding technologies that are independently assessed for introduction in an existing integrated product and manufacturing systems platform. The integrating systems are evaluated upon system maturity suggested by Sauser et al. (2006). The case is based on an interaction between two technologies. Each technology, or system description, is represented by a Configurable Component (Claesson, 2006).

The starting point of the illustrative example is a situation caused by a change of requirements: The jet engine manufacturer needs to increase the performance of the engine, which leads to a significant increase in temperature at the TRS. The increased temperature leads to higher thermal stress on the component, thus it will be reinforced by an increase of the material thickness to handle the increased stress.

The CCs define technology elements for both product and manufacturing systems. The increased temperature corresponds to an expansion of the bandwidth of the current platform and a number of new subsystems are formed to meet the new requirement. This corresponds to principle one of SBCE: *Map the design space*. Now, the number of solutions needs to be reduced in order to fulfill principle two of SBCE: *Integrate by intersection*. Previous studies by Levandowski et al. (2014b) and Raudberget et al. (2014) show how the number of solutions can be reduced based on relations between Functional Requirements (FRs), Design Solutions (DSs) and Constraints (Cs), using EF-M modeling. In this presented case, we further reduce the number of solutions by using information from manufacturing, forming an integrated product and manufacturing systems platform. The choice of manufacturing technology offers the potential to reduce the set of integrated product and manufacturing solutions based on manufacturing capability. In this way we address principle 3 of SBCE: *Feasibility before commitment*.

Using Maturity of Technologies to Compare Interacting Systems

The proposed methodology can support elimination of technologies in early phases of development by calculating and comparing system maturity for alternative solutions. It is made possible by assessing the independent maturity of product and manufacturing technologies using System Readiness Level (SRL) as a metric. The case company has several welding technologies available, Tungsten Inert Gas (TIG) welding, Plasma welding, Laser welding and Electron Beam (EB) welding. The capability of each welding technology is described in terms of TRL for defined bandwidths. In the integrated product and manufacturing platform it is possible to accommodate technologies spanning from different degrees of maturity. The platform is prepared to reflect the company's complete capability and assets, including technologies, requirements, interactions and trade-offs. As a firm's knowledge develops, new immature technologies will be advanced, whilst the platform should be elaborated.

An example of a trade-off curve, or rather a limit curve, for laser welding is shown in Figure 5, where the capability of the welding system with respect to TRL is shown as a function of welding speed and material thickness for a given alloy.

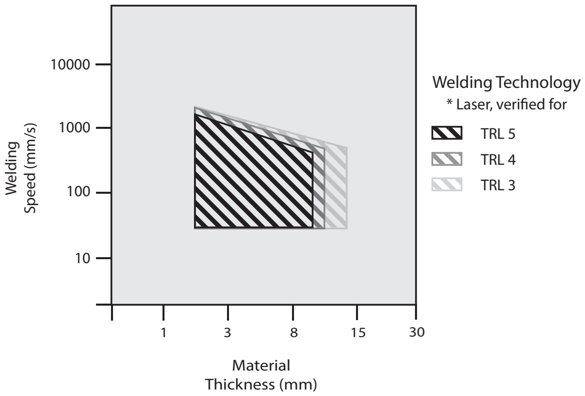


Figure 5: Example of a rich limit curve, illustrating a welding technology and its capability at various TRLs (redrawn and developed from Levandowski et al. (2014a)).

The aggregate capability of the welding technologies is illustrated by a limit curve in Figure 6.

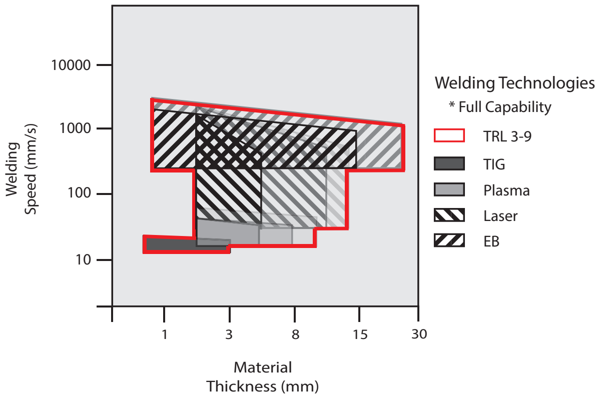


Figure 6: A limiting area describing the capability of various maturity levels of four unique welding technologies.

The concept of limit curves has here been further elaborated, expanding the concept to also include a maturity dimension. We suggest representing specific bandwidths as portions of the complete capability, marked with distinct TRLs as seen in Figure 7. Thus, a determined bandwidth of the complete capability is here represented by a pre-assessed value of TRL for each welding technology.

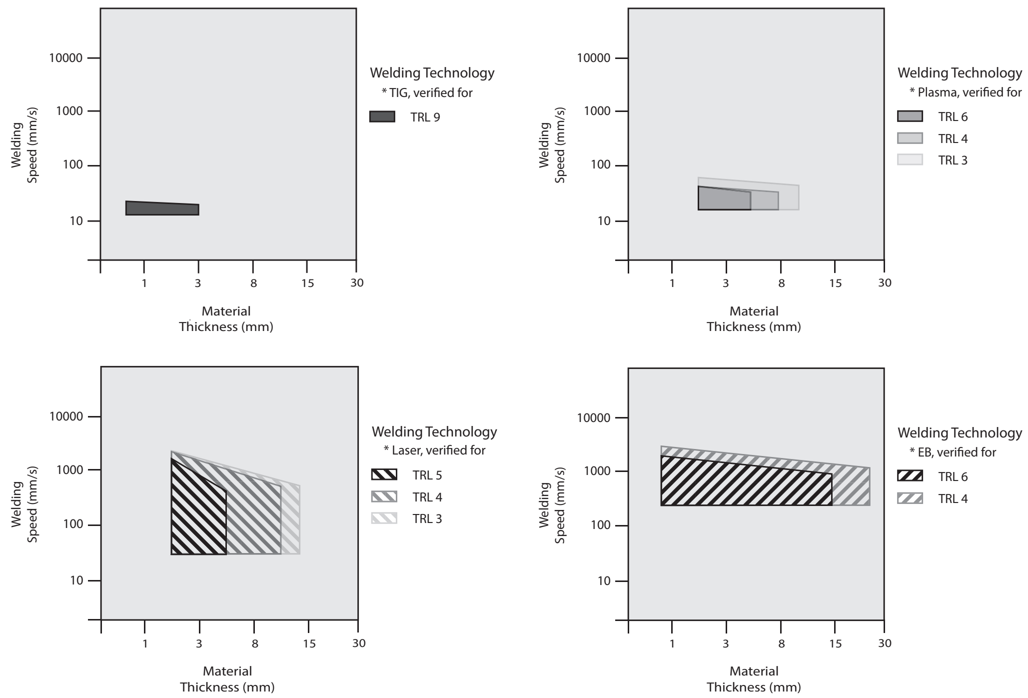


Figure 7: Rich limit curves and areas describing four unique welding technologies with specified capability bandwidths at different levels of maturity, plotting material thickness and welding speed.

Each of the four welding technologies has one distinct value of maturity (TRL) within a certain bandwidth of material thickness, illustrated by the rich trade-off curves presented in Figure 7.

The interaction maturity (IRL) was assigned by interpreting the IRL scale and the corresponding checklist suggested by Sauser et al. (2008). The framework of system maturity is applied by assigning a TRL level of the product technology and the welding technology. The calculation of the SRL value for each system holding a product technology and welding technology is given in Figure 8.

$$SRL_{(strut\ sys.)-(welding\ sys.)} = \frac{\frac{\begin{bmatrix} IRL_{(strut\ sys.)-(strut\ sys.)} & IRL_{(strut\ sys.)-(welding\ sys.)} \\ IRL_{(welding\ sys.)-(strut\ sys.)} & IRL_{(welding\ sys.)-(welding\ sys.)} \end{bmatrix}}{9} \times \frac{\begin{bmatrix} TRL_{(strut\ sys.)} \\ TRL_{(welding\ sys.)} \end{bmatrix}}{9}}{2}$$

Figure 8: The calculation of System Readiness Level (SRL) (adapted from Sauser et al. (2008)).

The application of the system maturity framework is illustrated in Figure 9, Figure 10 and Table 5.

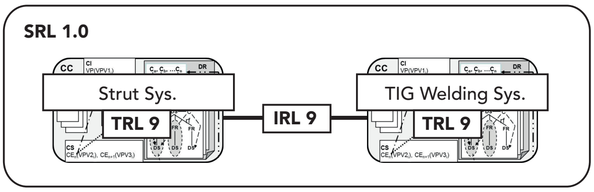


Figure 9: The TRS is produced, delivered and used in commercial air traffic. The maturity of product and manufacturing technologies is represented by independently assessed technology maturity (TRL) and interaction maturity (IRL) and a calculated system maturity (SRL), for a material thickness of 3 mm.

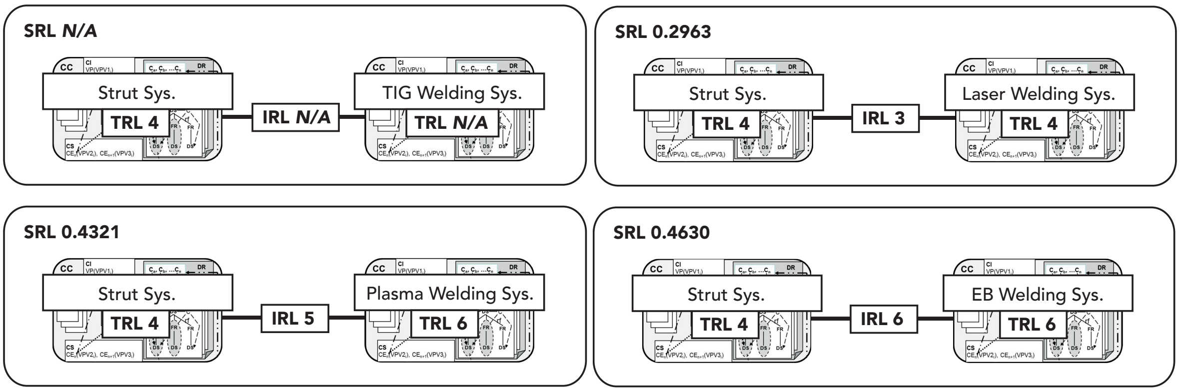


Figure 10: Conceptual phases of TRS development. Four system alternatives represented with independently assessed technology maturity (TRL) and interaction maturity (IRL) and the resulting system maturity (SRL) for the case with a determined bandwidth, here illustrating solely the material thickness of 5 mm.

The new determined bandwidth for the product technology, the four unique welding technologies and their independently assessed technology maturities, as well as their integration maturity and calculated system maturity are summarized in Table 5. To expand the width of the limited scope of this case, i.e. comparing system maturity, a more conventional comparison of welding technologies is introduced, namely a relative cost parameter.

Table 5: A summary of the calculated System Readiness Levels (SRLs) for both the TRS in use (material thickness: 3 mm) and for new concepts of a TRS illustrated by a scalable bandwidth (material thickness: 5-6 mm). Also, an elusive cost perspective is added to signify the importance of another important trade-off.

	Parameter	**Product Technology**	**Manufacturing Technology**			
	Material Thickness (mm)	Strut System	TIG Welding System	Plasma Welding System	Laser Welding System	EB Welding System
TRS in Use:	3	TRL 9	TRL: 9 IRL: 9 SRL: 1.0	*Not Used*	*Not Used*	*Not Used*
Conceptual Phases of New TRS: Determined Bandwidth	5	TRL 4	*Not Verified*	TRL: 6 IRL: 5 SRL: 0.4321	TRL: 4 IRL: 3 SRL: 0.4074	TRL: 6 IRL: 6 SRL: 0.5556
	6	TRL 4	*Not Verified*	TRL: 4 IRL: 5 SRL: 0.3704	TRL: 4 IRL: 3 SRL: 0.3704	TRL: 6 IRL: 6 SRL: 0.5556
Relative Cost of Welding Technologies:			$COST_{TIG}$ <	$COST_{Plasma}$ <	$COST_{Laser}$ <	$COST_{EB}$

DISCUSSION

Depending on the situation, if a decision has to be taken fast or if there is time for advancing a welding technology before preparing the production, the outcome of a decision is rather different. The TIG welding system has reached its internal complete capability bandwidth, and cannot longer be utilized for the new product system. The most suitable welding technology, according to the system maturity, is the EB welding system. However, the inclusion of the relative cost parameter advocates a high cost of manufacturing for the EB welding system. For this reason, it may be seemly to advance the capability of the Plasma welding system to a higher maturity level, which may imply less cost than the EB welding system.

The presented method can be used as support for making decisions on which technology to advance, and expand the capability bandwidth, based on assessment of alternative solutions of interacting technologies.

The interpretation of the IRL can be questioned, since the definition of an interaction described by Sauser et al. (2008) is strongly coupled with data and information. It is therefore suggested that the interaction definition should be expanded or reshaped to also reflect the application of other types of interactions. One framework that explicitly include the interaction of information is proposed by Pimmler and Eppinger (1994). This framework defines four interaction types: 1) associations of physical space, 2) associations of energy exchange, 3) associations of information exchange and 4) associations of materials exchange. The nature of the interactions are further elaborated by a five level classification scale: Required: (+2), Desired: (+1), Indifferent: (0), Undesired: (-1) and

Detrimental (-2). The interaction types above are promising augmentations of the SRL framework as well as for elimination of alternative DSs in an EF-M tree, following SBCE. This is therefore targeted for future studies.

CONCLUSION

The approach suggested in this paper addresses a problem in platform development where little has been explored. There is plenty of knowledge within the framework of platforms and, foremost, the scalability benefits in production, yet there are few who deliberate upon how to efficiently and accurately develop and find feasible concepts for a platform. This paper contributes with a new way of eliminating solutions based on system maturity, within a certain capability bandwidth. The approach is illustrated by a case from the aerospace industry and is based on platform theory, Set-Based Concurrent Engineering (SBCE) and system maturity.

The assessment method presented in this paper can support elimination of unfeasible integrated product and manufacturing solutions before technology commitment. It can be used by systems designers and managers to 1) evaluate the company status of capability and maturity with the use of rich trade-off and limit curves, 2) eliminate immature technologies within a certain capability bandwidth, and 3) prioritize advanced technology development initiatives with respect to risk of implementing manufacturing technologies to interact with a product technology. Thus, even if the maturity of the independent product and manufacturing technologies is high, the system maturity may be low.

Future work includes testing and validating the presented method on a larger system of an integrated product and manufacturing systems platform.

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REFERENCES

Berglund, F. & Claesson, A. (2005). Utilising the Concept of a Design's Bandwidth to Achieve Product Platform Effectiveness. ICED 05: 15th International Conference on Engineering Design: Engineering Design and the Global Economy. Engineers Australia.

Bruch, J. & Johansson, G. (2011). Dual Perspective on Information Exchange between Design and Manufacturing. International Conference on Engineering Design, ICED11.

Claesson, A. (2006). A Configurable Component Framework Supporting Platform-Based Product Development. Doctoral Thesis, Chalmers University of Technology, Gothenburg.

*Cooper, R. G. (1985). Selecting winning new product projects: Using the NewProd system. Journal of Product Innovation Management, 2***,** *34-44.*

DoD (2001). Systems Engineering Fundamentals. In: Defense, D. o. (ed.). Defense Acquisition University: Defense Acquisition University Press.

Johannesson, H. (2014). Emphasizing Reuse of Generic Assets Through Integrated Product and Production System Development Platforms. In: Simpson, T. W., Jiao, J., Siddique, Z. & Hölttä-Otto, K. (eds.) Advances in Product Family and Product Platform Design. Springer New York.

Johannesson, H. & Claesson, A. (2005). Systematic product platform design: a combined function-means and parametric modeling approach. Journal of Engineering Design, 16, 25-43.

Landahl, J., Bergsjö, D. & Johannesson, H. (2014). Future Alternatives for Automotive Configuration Management. Procedia Computer Science, 28, 103-110.

Levandowski, C., Michaelis, M. T. & Johannesson, H. (2014a). Set-based development using an integrated product and manufacturing system platform. Concurrent Engineering, 22, 234-252.

Levandowski, C., Raudberget, D. & Johannesson, H. (2014b). Set-Based Concurrent Engineering for Early Phases in Platform Development. The 21st ISPE International Conference on Concurrent Engineering - CE2014.

Levandowski, C. E., Corin-Stig, D., Bergsjö, D., Forslund, A., Högman, U., Söderberg, R. & Johannesson, H. (2013). An integrated approach to technology platform and product platform development. Concurrent Engineering: Research and Applications, 21, 65-83.

Magnaye, R. B., Sauser, B. J. & Ramirez-Marquez, J. E. (2010). System development planning using readiness levels in a cost of development minimization model. Systems Engineering, 13, 311-323.

Mankins, J. C. (1995). Technology readiness levels. White Paper, April, 6.

Mankins, J. C. (2002). Approaches to strategic research and technology (R&T) analysis and road mapping. Acta Astronautica, 51, 3-21.

Michaelis, M. T. (2013). Co-Development of Product and Manufacturing Systems Using Integrated Platform Models. Ph.D. thesis, Chalmers University of Technology.

Michaelis, M. T., Johannesson, H. & ElMaraghy, H. A. (2014). Function and Process Modeling for the Co-Development of Products and Manufacturing Systems. Journal of Manufacturing Systems.

Pahl, G., Beitz, W., et al. (2007). Engineering Design – A Systematic Approach, Berlin, Germany., Springer.

Pimmler, T. U. & Eppinger, S. D. (1994). Integration analysis of product decompositions, Alfred P. Sloan School of Management, Massachusetts Institute of Technology Cambridge, MA.

Raudberget, D. (2010a). The Decision Process in Set-Based Concurrent Engineering - an Industrial Case Study. 11th International Design Conference - DESIGN 2010.

Raudberget, D. (2010b). Practical Applications of Set-Based Concurrent Engineering in Industry. Journal of Mechanical Engineering- Strojniški vestnik, 56, 685-695

Raudberget, D., Michaelis, M. & Johannesson, H. (2014). Combining Set-Based Concurrent Engineering and Function-Means Modelling to Manage Platform-Based Product Family Design. Proceedings of the 2014 IEEE IEEM.

Sauser, B., Gove, R., Forbes, E. & Ramirez-Marquez, J. E. (2010). Integration maturity metrics: Development of an integration readiness level. Information, Knowledge, Systems Management, 9, 17-46.

Sauser, B., Verma, D., Ramirez-Marquez, J. & Gove, R. (2006). From TRL to SRL: The concept of systems readiness levels. Conference on Systems Engineering Research, Los Angeles, CA.

Sauser, B. J., Ramirez-Marquez, J. E., Henry, D. & DiMarzio, D. (2008). A system maturity index for the systems engineering life cycle. International Journal of Industrial and Systems Engineering, 3, 673-691.

Schachinger, P. & Johannesson, H. L. (2000). Computer modelling of design specifications. Journal of Engineering Design, 11, 317 - 329.

Sobek, D. K., Ward, A. & Liker, J. (1999). Toyota's Principles of Set-Based Concurrent Engineering. Sloan Management Review, 40, 67-83.

Ulrich, K. T. & Eppinger, S. D. (2012). Product Design and Development, Boston, Massachusetts, USA, McGraw-Hill.

Ward, A., Liker, J. K., Cristiano, J. J. & Sobek, D. K. (1995). The second Toyota paradox: How delaying decisions can make better cars faster. Sloan Management Review, 36, 43-61.