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TRENDS, OBSERVATIONS AND DRIVERS FOR CHANGE IN SYSTEMS ENGINEERING DESIGN

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Abstract

Manufactures, developing products, need to adapt and improve their practices taking advantage of technology advancements and simultaneously develop products and solutions to fit a new world. This paper discusses how societal and technological trends drive the need for change and evolution in what is called Systems Engineering Design (SED), indicating a systems view on engineering design. Through an analysis and selected examples it is argued that SED capabilities need to better address the width and complexity of design problem, takes advantages of increased computational power and sensing technologies to master future challenges. An important factor for successful deployment and change in industrial context, is the need for interactive and visual aids and easily accessible support methods. This can pave the way also for advanced SED support.

Keywords: Systems Engineering (SE), Design methodology, Early design phases

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1 INTRODUCTION

What is considered best practice in engineering design is constantly evolving, mainly due to new and changed business and societal needs and market competitiveness. Best practices are also impacted by advancements in both technologies that are designed and built into new products and technologies that enable new means and ways of developing new products. Increasingly complex products are being developed and provided using a wider range of constituent technologies.
A question is in what way means for engineering design and development are affected by this progress, and what new capabilities are needed to support future engineering product development?
The aim of this paper is to discuss and clarify expectations on engineering methods and tools used in development of complex products. Authors discuss expectations of a systems engineering design (SED) environment supporting an increasingly dynamic, global and complex development context.

2 METHOD

The fields of Systems Engineering and Engineering Design together with a sample of related methods and methodologies are briefly introduced, followed by outlining trends and challenges for what we chose to refer to as Systems Engineering Design, SED.
Societal and technology trends have been captured based on literature studies and worked through in an industrial/academic workshop with 30 specialists and industrialists, and they are summarized in this paper. Authors jointly analysed consequences and expected capabilities needed to address challenges and how to exploit advancements in technology. Selected results from recently completed research projects at the Wingquist laboratory at Chalmers University of Technology are analysed with respect to how they relate to the same challenges, and their contributions to the highlighted challenges. Finally, the impact on and consequence for advancing new and enhanced engineering methods, tools and processes are presented, and prioritized ways forward are outlined.

3 BRIEF REVIEW OF RELATED LITERATURE

Seeking ways to improve product development practice has been a topic for a very long time. Smith (1997) found that functional and manufacturing constraints need to be considered simultaneously, that knowledge sharing between different domains benefit through integrated design teams and that designers need to consider the end customers' expectations throughout the design process. In addition, time to market is a decisive factor for success. All these conditions prevailed already 100 years ago and have clearly inspired development of methods, tools, theories and practices since then.
The term Systems Engineering (SE) was supposedly coined at Bell Laboratories in the 1940s. SE soon became a necessary means to organize complex, advanced products and projects. Capabilities developed within SE ranges from information standards and development logics to a vast number of means for systematically dealing with multiple aspects of an organisation. INCOSE (2016) expects this development to continue and in their vision for 2025 predict that societal needs will bring an increasing diversity of aspects that needs to be considered. They also believe that there will be a greater diversity of technologies to integrate and an even more diverse workforce which relies heavily on computer support tools. Although SE has been extensively used for complex product development, it is yet not predominant in the actual design and sizing of products and components. Model Based Systems Engineering (MBSE), see e.g. Piaszczyk (2011), has gained popularity as a means to organize and design complex systems, with the prime focus on modelling the requirements and verification process and the overall system behaviour. A limitation is the link to and possibility to integrate the detailed, embodied technologies, and MBSE has not been extensively combined with geometrical and physical engineering design models.
A related domain is Engineering Design (ED), which is the systematic process of creating products, systems and services. ED has been extensively researched for decades resulting in increasingly advanced ways of describing the products themselves as well as the product creation process. Pahl et al. (2007) developed their well-known systematic approach to guide industry, manifested in the VDI guidelines 2221 and 2222. Driven by European initiatives, the Theory of Technical Systems (TTS) was brought forward as a means to establish ED as a scientific discipline (Eder, 2011) covering both the underlying structure of the artefact (what) and the process of engineering design (how). One aspect of TTS is that

it provides the necessary basis for creating models to represent many different facets of the design. The purpose of these models range from visualization to analysis. Common for models used in systems engineering design is the aim to create an understanding to support decision making. The models may for example represent customer requirements, physical parts or manufacturing processes. The Chromosome Model by Andreasen (1992) presents several different design elements from a number of domains. The model connects concrete parts and subassemblies used to create product structures to abstract product representations, i.e. functions, processes and organs. Although these concepts have influenced engineering design methods and practices, few industrial tools have directly been modified to use the constructs provided. Another approach to ED is axiomatic design by Suh (1990), who proposed and built applications based on two axioms, and the Design Structure Matrix (Steward, 1981), focusing on representations of dependencies between components. Further, Set-Based Concurrent Engineering (SBCE) se e.g. Ward and Sobek (2014) as a reaction on the practice of selecting a single concept early in the process, so called Point-Based Design (PBD). SBCE promotes the study of a set of solutions within a solution space and emphasises knowledge creation along the development process. It has three principles (Sobek et al., 1999): i) map the design space, ii) integrate by intersection, and iii) establish feasibility before commitment. Axiomatic Design, DSM and SBCE have gained significant attention and acceptance (Browning, 2016) in both Engineering Design and System Engineering domains.

Engineering Design of complex products is normally conducted in product development projects in large organisations and there is a need to facilitate also how to organise the development work. A classical challenge (Smith, 1997) is for engineers focusing on ensuring functionality of products to simultaneously collaborate with production engineers to make the products fit for manufacturing. Concurrent Engineering (CE), see e.g. Prasad (1996), addresses concurrency between design and manufacturing.

An approach commonly applied to achieve an efficient process is platform-based design and development. This is a way to reuse design knowledge for mass customization. In a platform it is possible to reuse a wide range of assets (Robertson, 1998) or subsystems and interfaces (Meyer and Lehnerd, 1997). Platforms are commonly modelled as physical modules and their respective configuration rules, but recent approaches move towards more abstract models, for example functional models to represent different technologies (Alblas et al., 2011) and concepts. Platform based development has also been extended to include reuse of production resources and knowledge (Levandowski, 2013).

Another aspect is that product development and engineering design is about decision making, and the idea that well-informed decisions are better than the opposite. "Knowledge" become central, and industries generate that either through experiences from problem solving in product development projects or in R&D activities and/or operational development initiatives. Whilst knowledge is often of a tacit nature and deals with (personal) interpretation of information, the ways to make it explicit and shareable within an organisation are not straightforward. The knowledge is often not well documented, sometimes not at all, when a busy design team rushes to the next project, but since it is a valuable asset it should be recorded, further developed and reused as much as possible (Ward and Sobek, 2014). A key challenge is to have an easy to use and interactive support that can provide the knowledge when it is needed.

Finally, there is a movement to strengthen the notion of Value Driven Design in complex product development. Paul Collopy has promoted quantitative value aspects as drivers for development to balance the established focus on cost in industry (Collopy and Hollingsworth, 2011). In the European aerospace industry Value Driven Design has been further developed and integrated with engineering design (Kipouros et al., 2014), and as a part of this effort it is now represented in the information model MOSSEC (2015). A key feature here is the introduction of a Value Creation Strategy with a prioritized set of stakeholder needs that constitute the high level objective and guides the search for design solutions.

In conclusion, we noticed a lack of methodological support for synthesising complex systems designs as well as methodologies which from the start were designed with advanced computational support as the backbone. This calls for a closer look at the factors that may drive the design of an enhanced methodological support for design.

4 DRIVERS FOR CHANGE

For simplicity, the drivers for change are introduced from two complementary perspectives. The society, in which we all act, and selected trends in technology.

4.1 Society in change

Our society provides the foundation for everything we do, covering social, environmental and business changes, and it is in constant change at an increasing pace. Engineering plays an important role in shaping the future, and engineering designers and product developers need to develop new products and solutions that meet the needs. In the United States, the National Academy of Sciences has issued a list of 14 grand challenge themes for engineering in the 21st century (NAE, 2008), and in a first workshop in Luleå in January 2016 between industrialists and academics in Sweden, a number of trends were identified. These are compiled in Table 1 for the purpose of discussion in the industry/academy workshop at Chalmers in November 2016, where the challenges for Systems Engineering Design was discussed.

Table 1 Trends and their impact on Systems Engineering Design in product development

Trends & phenomena	Challenges for Systems Engineering Design
1. Unbalanced use of natural resources	Difficult to embrace the width necessary to avoid sub-optimization and accurately predict life cycle behaviour in design phases (Hallstedt, 2017).
2. Shifting energy transformation	The way we produce and transform energy is in transition, see e.g. (Rosenkranz, 2015), where new products will deploy completely novel technologies for e.g. vehicle propulsion.
3. Automation in Engineering Development	Advancements within ICT domain drive automation in all aspects of engineering (Weyrich, 2014). A challenge to explore and visualize design spaces.
4. Cognitive capacity and continuous learning	"We do no longer have the time to gain the experience we need to make wise decisions". The pressure in industry to learn and adapt is a challenge for the engineering work force." Easy to use and learn" means and aids for SED need to rely on viable and sustainable principles and theories.
5. Knowledge Transformation	Product Development needs to increasingly find, create, use, and reuse knowledge that already exists.
6. Servitization	Product Development need to develop solutions including services, since user(s) of products value the effect and experience of what the products do, rather than ownership of goods.
7. Combinatorial Explosion	Individualization in combination with complexity of solutions (combined hardware, software, etc.) offered globally results in an explosion of possible combinations of complex products.
8. Multi disciplinarity of innovations	Innovative functionality and appearance of products require a mix of technologies from different domains. Decisions need to simultaneously account for disparate aspects.
9. Radical vs Incremental Innovation	Our ability to optimize and refine mature designs through engineering risk taking to increase the gap to assess and promote radical, high potential, innovations.

The list above is brief and non-exhaustive, yet illustrates the influences that trends have on the means to carry out systems engineering design in product development. In the workshop, it was concluded that the presented trends do impact the means engineers use for development and should be explored in more detail.

4.2 Technology in change

The breadth of advances emerging in technology is exhaustive. Technologists see it as a maturation of a stream of new technologies, impacting both current and future products (Gartner, 2016). Meanwhile technology advances, in particular in the ICT domain, provide significant opportunities also for SED means.

Technologies may be of a disruptive character, where their integration into systems require new phenomena to be designed. Additive manufacturing and 3D printing offer new ways of realizing ideas and are attractive since they increase the design freedom using topology optimization and reduction of material waste and thereto promise to shorten the design-to-build cycle. But they also come with new constraints, such as the scalability into higher production volumes and qualification of high performance applications. Internet of Things (Vermesan, 2013) technologies offer products to be monitored and remotely controlled and give raise to new innovative products such as personal health diagnostics tools and more. Technologies within the energy domain provide increasing opportunities to move away from the carbon-based economy using solar, wind, wave and other sources of natural and environmentally friendly energy. Technologies to store, transport and transform energy also emerge in large scale installations, such as powertrains in cars.

Today's engineering designers and product developers are provided with a rich set of tools to solve design problems. Innovative products and applications are brought forward, and the engineering teams previously dominated by mechanical and electromechanical designers are now faced with an integral set of advanced, manufacturing process-dependent materials, in combination with sensors and software solutions that combine technologies from fundamentally different disciplines. In addition, servitization in business has resulted in ever tighter interaction and responsibilities for the product while in use. Aids such as CAD and CAE tools have predominately been brought forward from within specific disciplines, and Product Life Cycle Management (PLM) tools (implemented in industries) often rely on underlying logics and product structures not made to master the more rich and dynamic, multi-disciplinary environment which is already a reality.

Advances in technology also bring new capabilities into the aids that support SED. The computational power continues to increase, allowing engineering teams to increase fidelity in analyses, capturing more physics in early phases. In combination with engineering automation techniques it is also possible to create digital experiments to explore a range of design variants. Computer graphics and touch screen technologies etc. enable a more direct and interactive dialogue within the design team and with its' stakeholders. Cloud computing offers the ability to share information resources for storage and computation and more. Such technologies are necessary to facilitate the already globally distributed way of performing product development.

In summary, advances in technology affect both what is being developed and how it is being developed. The ability to trade and integrate new technologies from different domains becomes critical for OEM's of complex products, and the ability to insert disruptive technologies into new product concepts becomes critical for suppliers and technologists. Advancements in ICT for design support will enable digital experiments already in the design phase.

5 SYSTEMS ENGINEERING DESIGN

Below, the authors introduce Systems Engineering Design (SED) as a concept to combine the strengths of SE and ED, i.e. to manage the overall system behaviour while integrating and designing components and technologies.

5.1 The concept of SED

SED aims to provide a coherent set of methods, tools, processes and models that will enable a computational and systems-oriented as well as detail-informed treatment of more complex and heterogeneous design problems than the current approaches allow for. Computational support is pervasive throughout the system lifecycle, including synthesis, analysis, verification, and monitoring of use. SED has two capability dimensions for the design of complex products: a process dimension and a model dimension.

The ***process dimension***, recently used as a means to organize engineering capabilities within aeronautics (TOICA, 2016), includes the four phases of discovering, assessing, defining and evaluating solutions to design problems from a systems perspective. These phases are overlapping and highly iterative and can be seen as a "classical" divergent-convergent design process aiming at identifying and developing the most appropriate design solution.

- **Discovering** is characterized by understanding and framing the design problem and space and seeking candidate solution elements, with the intent to systematically explore many candidate solutions.

- **Assessing** is characterized by the first screening of the feasibility and compliance with the design space. Findings are used to develop both the allowable design space and the preferred solution regions.
- **Defining** deals with the effort to clarify, add detail and define allowable solutions.
- **Evaluating** addresses the analysis and reduction of the number of feasible options based on an analysis of their performance and behaviour.

The ***model dimension*** is associated with a platform-based development approach. Platform-based development in this context relates to the ability to explore design solutions in a family of products. It is also about the ability to learn, adapt and continuously advance knowledge within a specialization domain through capturing experiences from ongoing product development projects, feedback from products in use and systematically gaining knowledge from research and technology development.

5.2 Expected capabilities of SED support systems

What do we then expect from a systems engineering design and development environment of tomorrow? Following the trend workshop, the authors identified 8 different capabilities, suggested to be critical for forthcoming Systems Engineering Design support. In Table 2 below, a set of expected capabilities for a modern design and development support system is listed and commented on.

Table 2 Expected capabilities for systems engineering design support system

	Expected capabilities	Comment
1	Discover alternative solution elements and solution element variations	Computer aided generation/synthesis of design solutions, including variations with respect to realizing physical effects, structure, form and material.
2	Balance and optimise impact on system behaviour from multiple disciplines	Disciplinary design systems will be superior to generic design systems within their domain, so a heterogeneous approach is needed. Ability to coordinate such design tools in discovery and assessment phases is limited today.
3	Enable definition and analysis of life cycle behaviour	From development of products to development of solutions, including the life cycle behaviour. Manufacturers take a greater responsibility for and business interest in their product through its life and need to design solutions for this situation.
4	Enable assessment of physical and functional performance already when exploring a configure design/solution space	At present, the breadth of solutions as candidates in a design space is often much wider than what is practically possible to resolve in detail. There is a need to better represent the level of detail and information to be able to make informed decisions.
5	Gain knowledge and validity through usage (learning)	The investments made in R&D as well as when producing, using and maintaining products provide essential knowledge also for future products and solutions. Our ability to capture and reuse this information and knowledge is low, yet important for decision making.
6	Facilitate understanding between people and organisations with different expertise	Solutions based on mixing competences and disciplinary contributions require better organisation, sharing and interaction between tools, methods, people and organisations.
7	Capitalise on advancements in ICT	Computational power and smart sensor technologies provide new opportunities for SED, in that large and complex sets of information can be generated, processed and analysed. Current theories and models for SED have historically not been set up for this scenario.
8	Visualise complex system characteristics	Complexity and data richness need to be possible to visualize to provide the necessary information for decision making. Such an overview must also be dynamic and interactive and support distributed development.

6 EXAMPLES

Several examples are presented, each focusing on strengthening the decision-making ability through improving the knowledge base, either through sharing experiences and introducing new methodologies or by enabling advanced simulation tools to be integrated to simultaneously address different disciplinary aspects.

6.1 Facilitate understanding of new design tools and use of advancements in ICT

The importance to gain acceptance and enable adoption of improved design methods often relies on how the effort to adopt in a busy industrial setting and the large amount of ill structured information can be compiled. A new method named Instant Set-Based Design (ISBD) (Ström et al., 2016a, Ström et al., 2016b) was developed and tested to facilitate introduction "in a day".

The method uses concept creation methods such as the 6-3-5 method, the gallery method and morphological matrices to generate concepts. User groups use visual aids to communicate ideas and discuss weaknesses and strengths of different concepts. The concepts in the design space are explored and evaluated, knowledge gaps are identified and weak solutions eliminated. The method is carried out as a workshop in which concepts are sketched on A3 paper and discussed. The entire process is carried out during one work day with a couple of hours of preparation. ISBD was tested in four industrial cases with positive results such as instant knowledge sharing. The industry participants have continued to use the method after the initial research pilots.

The other aspect is how to make use of the vast amount of ill-structured data and information captured in the operational process. In a recently launched study together with the Volvo Group, Arnarsson et al. (2017) conducted interviews with a heterogeneous group of engineers involved in a large and complex product development project and identified their need for data mining and data analysis. Although organisations such as Volvo has been aware of this potential for a long time, the emerging Big Data Analysis capabilities open new opportunities to make use of this information both for new design and evolving (incremental) design. How to integrate these sources of knowledge into useful design methods and tools is of interest both scientifically and industrially.

These examples display the interest and impact on primarily capabilities 6 and 7, in Table 2.

6.2 Quantified assessment through integration of multiple design and analysis tools

Computer and ICT advancements have substantially increased the ability to virtually model and analyse designs. Expert tools have enabled analyses of a multitude of aspects whereas integrating tools from different disciplines has been a challenge. The disciplines are commonly separated and analyses are conducted during the late development phases when one or a few concepts are detailed. These tools are traditionally integrated in large all-inclusive systems. Yet, in order to explore an abundance of concepts and technologies and find feasible ones during the early phases, new approaches are needed. Landahl et al. (2016) show, in an example from the aerospace industry, how different expert systems can be integrated to assess producibility of a large set of different concepts using an integrated platform approach that includes information of envisioned product variants and available manufacturing resources. Instead of including all systems in one master, the expert systems are called upon request and the analysis results are collected to support design engineers in making a final evaluation. The approach enables set-based concurrent engineering by providing a solid base for design space mapping and elimination of unfeasible concepts based on producibility.

The example directly the interest and impact on capability 2 and 4 in Table 2 primarily.

6.3 Facilitating knowledge sharing in a distributed design organisation

Access to knowledge for decision making is critical (challenge 5). Ćatić and Malmqvist (2013) identified a bottleneck related to knowledge reuse where essentially the format in which knowledge is captured (typically through long documents for design guidelines and standards) had a negative effect on knowledge reuse as it required too much effort on the part of the knowledge consumer. They developed a method called engineering checksheets for managing knowledge based on simple checklists. This has been widely adopted in several engineering functions of a large automotive manufacturer in Sweden. The number of checksheets in this company has been steadily growing from 15 in 2014 to 50 in 2015 and over 100 in 2016. There are checksheets related to components, systems and processes which are maintained by cross-functional and cross-geographical teams on a continuous basis. As soon as new knowledge with respect to a component, system or process is discovered, it is used to update the checksheet. The design of the checksheet forces the knowledge suppliers to clearly connect the knowledge to its' context of reuse. Simultaneously, the checksheets are used and followed up as design references by teams in ongoing projects, and new, highly contextualized knowledge reaches them as soon as it is formalized through this channel.

Promoting a high degree of interactiveness and visual appearance to increase frequency of use in a daily environment has been proven to be a success factor, and benefit can be systematically gained through closing associated knowledge gaps (Ćatić, 2010). Visualizing a knowledge gap increases the possibility of keeping focus on it and in this way, increases the possibility of closing it.
Another use of visual approach to support a distributed way of working is the Lean Product Development method Visual Planning for remotely located teams. Based on a whiteboard and with post-its it has been very successful in local teams. Obstacles have however occurred when teams are not co-located (Lindlöf and Söderberg, 2011). Recent research has explored digital techniques for visual planning supporting distributed teams which have proven to be successful in replacing the traditional method (Stenholm et al., 2016).
Another study, examined digital vs physical lean tools and methods (Kaya et al, 2015). The results show that physical tools have low barriers-to-entry but that they lack the capabilities of digital tools. Hybrid tools (i.e., digital backbone with a physical user interface) combine benefits of physical and digital tools but lack a two-way information transfer (i.e., physical to digital and digital to physical). Digital solutions that employ a lean user interface are easy to learn and to use, they do not distract users from using the method and they bring all the benefits of digitalization (e.g., capturing knowledge, data mining, sharing-collaborating etc.).
In summary, the introduction of highly interactive and visual aids for sharing and managing knowledge has been successfully demonstrated, and industrial adoption beyond the research studies support these arguments. These studies support challenges 5, 6, 7 and 8 in Table 2.

6.4 Assessment of value by alternative options

Choosing the right concept is essential for the success of the product. Computer tools are used to help designers in assessing different aspects of the product to make better design decisions. Collectively, these aspects contribute to the total value of the product (Collopy and Hollingsworth, 2011). Properties such as mass and stresses are commonly covered by CAD and CAE software, whereas other value dimensions such as design complexity and how well the product integrates with other systems are scarcely supported, especially in pre-embodiment architectural phases. However, recent advances in functional modelling have proven feasible in discovering, defining, assessing and evaluating architectures in early phases, before CAD models are created (Raudberget et al., 2015). This requires trade-offs between value dimensions such as integration-ability and design process efficiency. The modelling of multiple architectures as function-means trees enables rapid configuration of variants, which can be translated into Design Structure Matrices (DSMs). These can be analysed through change propagation algorithms to create quantitative data to assess integration-ability and design process efficiency. The studies support challenges 1, 2 and to some extent 3.

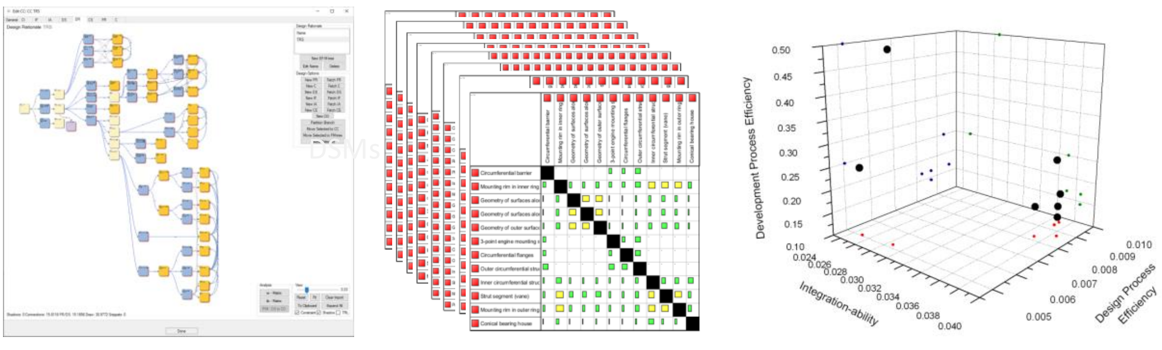

Figure 1: Architectures modelled as function-means trees, transferred into DSMs and assessed in a change propagation tool. The evaluation is made in three value dimensions.

6.5 Modelling objects and dependencies within a system

In a recent project a Causal Map was used by ASSA ABLOY to visualise complex system characteristics and to facilitate the dialogue in the design teams (Gustafsson et al., 2016). It helps engineers understand the relation between performance parameters, design parameters and application parameters.

This approach capitalizes on the cognitive ability to visualize dependencies and overall behaviour. In the specific case, the method was both simple and effective, and a good example of how a systems engineering design approach does not necessarily need a complex IT tool. A Causal Map forces the user to find out how different product properties interact, which of them influence each other and how they do that. Besides this basic and original use, the map can also be used to visualize where knowledge of these relations exists and where it is missing. Some knowledge gaps in a design are probably critical, meaning that it is risky to proceed beyond them with the design work until they are bridged, while other knowledge gaps are not critical. It is important to clearly distinguish between the two types of missing information and be aware of and act to bridge the critical knowledge gaps.

The Causal Map was found useful for facilitating understanding between e.g. sales force and customers when discussing product functions and important properties and what is possible to change in the design to alter them (Gustafsson et al., 2016). This addresses challenge 6 in Table 2.

7 CONCLUDING DISCUSSION

Through the samples of research provided we have identified three categories that together contribute to the success of new SED means. The examples reviewed in this paper support several observations made by Smith (1997) when advancing practices for product development.

First, taking advantage of the capabilities within ICT. Most established ED methods were developed in times of less powerful ICT support. Both computational power and ability to gather data in experiments and practice through sensing and condition monitoring has resulted in a great capability to deal with data also during design. ICT provides commercially available techniques that enable developments teams to use interactive and visual techniques. Developing and tailoring theories, practices and tools to benefit from the data is a strong driver in the search for improved practices.

Also, the importance of learning and understanding the available means. We have seen that an introduction of highly capable concepts for e.g. SBCE and Design Intent benefit from being introduced in a simplified manner, see e.g. the introduction of checksheets and causality maps.

For future work, we see the need to advance SED practices to better cope with the breath and complexity of the business and societal context we live in. Engineering tools and techniques, primarily quantitative and simulation driven technologies are powerful but not mature to handle disparate dimensions and complex problems requiring multi-disciplinary engineering.

Authors recognize that the importance of integrating technologies from different disciplines increases, as do the ability for technology providers to insert their technologies in new type of product contexts. The capabilities needed are reports from a first workshop and initial analysis. Yet they indicate that the driving conditions are important to understand for future capabilities for new product development.

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