International Journal of Lean Six Sigma, Volume 13, Number 4, 28 July 2022, pp. 824-846
DOI:10.1108/IJLSS-10-2016-0061

Physics-based Trade-off Curves to Develop a Control Access Product in Set-based Concurrent Engineering Environment

Zehra Canan Araci , Ahmed Al-Ashaab , Cesar Garcia Almeida

Abstract

Recently, companies have recognised the need to improve their product development activities. Designers face several challenges, especially, in the early stages of developing a new product. These challenges could be addressed by set-based concurrent engineering (SBCE) process model which is a core enabler of the lean product development approach. During the SBCE process, it is essential to have a right knowledge environment in order to achieve a robust optimal design. One of the quality improvement tools of lean product development is trade-off curves (ToCs). ToCs provide this knowledge environment by creating and visualising the knowledge based on the physics of the product. This paper aims to present a process to generate physics-based ToCs to facilitate lean product development processes by enabling two key activities of SBCE process model that are 1) Comparing alternative design solutions, and 2) Narrowing down the design set. Developed process of generating physics-based ToCs has been demonstrated via an industrial case study which is a research project. Findings of this application showed that physics-based ToC is an effective tool to enable SBCE activities as well as to save time and provide the required knowledge environment for the designers to support their decision-making.

Keywords: lean product development, set-based concurrent engineering, trade-off curves, physics knowledge, knowledge creation and visualisation, electronic card reader.

1. Introduction

Today's global competitive world pressurises companies to release new products into the market faster and with better quality than their competitors. This situation leads them to improve their product development processes to be able to respond to the customers' demands. Lean product development is an effective approach to decrease time-to-market as well as enhance product innovation to be produced in good quality and a cost effective manner (Gremyr and Fouquet, 2012; Khan et al., 2013; Liker and Morgan, 2011; Sobek et al., 1999). Set-based concurrent engineering (SBCE), which is a core element of lean product development, is a knowledge intensive process considering a set of designs concurrently and then aggressively narrowing down the set, helping to ensure that designs are feasible and compatible with their environment (Khan et al., 2013; Levandowski et al., 2014; Ward and Sobek II, 2014; Yannou et al., 2013). SBCE dramatically reduces the need for engineering changes (Khan et al., 2013). Additionally, this set-based philosophy helps identifying and resolving problems as early as possible and ensures that product attributes, including crucial trade-offs, are clearly understood (Al-Ashaab et al., 2013; Morgan and Liker, 2006; Ward and Sobek II, 2014).

A knowledge-based environment is one of the most important requirements for a successful SBCE implementation. One way to provide this environment is the use of trade-off curves (Araci et al., 2016; Correia et al., 2014; Raudberget, 2010). Although trade-off curves are considered to be very efficient tools, the context was not defined

Published by Emerald. This is the Author Accepted Manuscript issued with: Creative Commons Attribution Non-Commercial License (CC:BY:NC 4.0).
The final published version (version of record) is available online at DOI:10.1108/IJLSS-10-2016-0061. Please refer to any applicable publisher terms of use.

well (Oosterwal, 2010). Therefore, scholars have focused on defining principles and practices in order to generate and to use generated trade-off curves within SBCE process model (Araci et al., 2016). The early findings of a recent research (Araci et al., 2016) indicate that trade-off curves could enable five key activities of SBCE that are 1) identifying the feasible design area, 2) generating a set of designs, 3) comparing the alternative design solutions, 4) narrowing down the design set, 5) achieving the optimal design solution.

It is worth mentioning that there are three types of ToCs (Araci 2017): knowledge-based, math-based and physics-based. Knowledge-based ToCs are generated by using the historical data based on facts and knowledge obtained from mainly previous projects. Math-based ToCs are generated by using the data output resulted by mathematical modelling (Browning and Eppinger, 2002; Fine et al., 2005; Panduro et al., 2006; Richards and Valavanis, 2010; Roemer and Ahmadi, 2004). Physics-based ToCs are generated by using the data that is obtained by studying and understanding the physical characteristics of the product under development. Physics-based trade-off curves (ToCs) have the capability of creating physics knowledge that designers could see the conflicting relationships between different variables and make their decision on the optimum design which shows a better performance under certain circumstances. Therefore, the aim of this paper is to demonstrate a systematic approach for generating ToCs based on physics knowledge of the product in order to compare design solutions and narrow down the design sets which are two key activities of SBCE process model as mentioned above.

The remainder of this paper is structured as follows: The next section presents the applied research approach briefly. Section 3 summarises the extensive literature review that has been accomplished related to the importance and the role of trade-off curves within SBCE context. After that, the process of generating physics-based ToCs has been presented in detail which is developed by the information gained from the literature review, the industrial applications and feedback from the industrial collaborators. In Section 5, an industrial case study validation of the process has been demonstrated step by step through using realistic data in the development of a card reader that is a part of an electronic access control system. Findings have been discussed and benefits of physics-based ToCs for SBCE are highlighted in Section 6. Finally, in Section 7, conclusions and future work have been presented.

2. Research Approach

The adapted research approach for this paper consists of three phases: review of the related literature, developing the process of generating physics-based ToCs, implementing the developed process in an industrial case study for validation.

In the first phase, related literature was reviewed extensively by capturing the best applications and practices of knowledge provision and visualisation. The role of trade-off curves within the SBCE process was also identified. During a product development process, organizations encounter challenges and create wastes. Rework is one of the common wastes occurs due to the last-minute changes in customer or design requirements (Khan et al., 2013). On the other hand, communication between different stakeholders of the product development becomes challenging due to lack of knowledge (Correia, 2014). Lean product development (LeanPD) can eliminate the waste

through developing a design-set with the use of the SBCE process model while ensuring the product innovation with high quality. Additionally, LeanPD addresses the communication challenges through knowledge creation with trade-off curves. Therefore, in this paper, LeanPD model was used as a methodology in the implementation of SBCE and ToCs. Authors, also, used the available databases in order to access academic publications in the subject area of this paper. In addition to that, industrial perspective on generating and using trade-off curves was captured through semi-structured interviews with engineers, designers, managers and senior managers from five different companies in the automotive, aerospace and engineering sectors. Findings of the literature review and industrial applications have been demonstrated in Section 3.

In the second phase, the output of the first phase helped authors develop a process of generating physics-based trade-off curves which addresses the needs of practitioners during their product development activities. SBCE process model, developed by Khan (2012) shown in Figure 2, has been selected as a lean product development approach in order to demonstrate the use of physics-based ToCs.

Finally, the proposed process of generating physics-based ToCs to enable SBCE has been validated using an industrial case study in a research environment of SME (Small and Medium-sized Enterprise). The product under development is a card reader that is the part of an electronic access control system. Authors used some tools in order to accomplish the tasks of the process throughout the implementation. Excel is one of these tools which used to store the obtained data and to generate trade-off curves. In order to perform structural and thermal analysis of the product under development, Ansys was used by the authors.

3. Review of the Related Literature

3.1. Overview of trade-off curves

Trade-off curve is a tool to visualise and trade off the relationships between conflicting factors/parameters/elements to help engineers make a robust and optimum decision (Bitran and Morabito, 1999; Otto and Antonsson, 1991). The most relevant definition to this paper's context has been made by Sobek et al. (1999): A trade-off curve establishes a relationship between two or more design parameters which is more useful than trade-off data. To clarify, it can be said that during the conceptual design stage, there are several conflicting parameters which have a major impact on design decision-making. Thus, it is important to identify these conflicting parameters and understand the relationships between them in a visual manner (Correia et al., 2014; Kennedy et al., 2014; Maksimovic et al., 2012). This is very important in the application of SBCE in order to produce a set of design solutions; as there are more design parameters to be considered simultaneously (Kennedy et al., 2014; Sobek et al., 1999). Therefore, trade-off curve is a useful tool to be employed in this context.

The review of the literature highlights the following key elements in order to develop suitable trade-off curves to support product design and development (Burke et al., 1988; Catalão et al., 2008; Hong et al., 2004; Kennedy et al., 2014; Kerga et al, 2014; Levandowski et al., 2014; Maksimovic et al., 2012; Ringen and Holtskog, 2013):

Customer requirements: These are the minimum requirements to satisfy stakeholders' needs. Figure 1 illustrates how customer requirements could be used in trade-off curves to identify the feasible area. In this example, there are three customer requirements which are illustrated with the dotted lines.

Decision criteria: These are related to customer requirements that drive the key design decisions. For example; cost and number of production; emissions and fuel consumption.

Design parameters: Those are the ones that give the special characteristics of the product under development. The different design parameters might be conflicting with each other. Therefore, they need to be studied and analysed to understand the relation to each other and identify the area of conflicts and the reason behind that. Examples are material cost against the number of production, noise level against overall product size and fuel consumption against pollution. Figure 1 shows how design parameters are presented as X and Y axes.

Design parameters data: Ranges of data of the identified design parameters need to be captured from for example; previous projects, testing and simulation. Figure 1 illustrates how design parameter data is plotted against X and Y axes. Thus, this data is represented in a visual format of design solutions by ToCs.

Feasible area: The area that is defined by plotting customer requirements against the design parameters. This is to identify possible conceptual design solutions that meet both the decision criteria and the customer requirements for the related project. In the hypothetical example shown in Figure 1, six potential solutions have been found within the feasible area which is surrounded by three customer requirements.

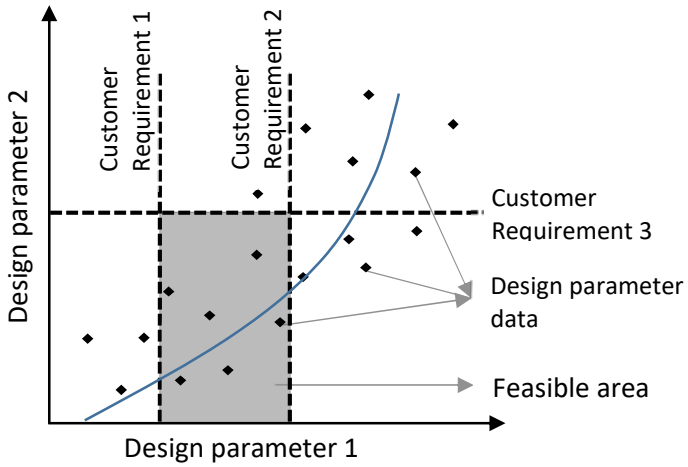


Figure 1 An example of trade-off curves illustrating the key elements: design parameters 1 and 2 are presented on X and Y axes; design parameters data is plotted against two axes; three customer requirements are plotted against the trade-off curves to define the feasible area.

ToCs could be generated in two dimensional, three-dimensional or multi-dimensional forms depending on the need or different type of products. For example, if the design team would like to see relationships between more than two design parameters in order to make a more accurate decision, these relationships could be visually projected on a three-dimensional or multi-dimensional ToC.

Trade-off curves have been widely used in the literature, especially from the 1960s (Pershing, 1968), within a range of disciplines from finance and environmental science to engineering and computer science. Most of the studies in these disciplines have used trade-off curves to facilitate solving multi-objective optimisation problems. Multi-objective optimisation problems (or multi-criteria) are the problems that have more than one conflicting objective functions to be satisfied in order to achieve the optimum solution (Askar and Tiwari, 2011). The common subjects that use trade-off curves to facilitate solutions of multi-objective optimisation problems are: Manufacturing networks optimisation (Bitran and Morabito, 1999), scheduling (Catalao et al., 2008), capacity planning and resource allocation (Bretthauer et al., 2003), and inventory management (Grewal et al., 2014). The highlighted roles of trade-off curves within these studies are: Decision support (Holtzman, 1984; Preetha Roselyn et al., 2014), data representation and visualisation (Abido 2003; Rhyu et al., 1988), best solution compromise (Avigad and Moshaiov, 2010; Mohagheghi et al., 2014; Zhao et al., 2011), comparing conflicting parameters (Dunning et al., 2014; Kuo et al., 2014), comparing solutions (Gardner and Everette, 1990; Quirante et al., 2013; Suwanruji and Enns, 2007), and feasible/infeasible area definition (Cao and Yang, 2004; Samarasinghe et al., 2013). However, these trade-off curves are developed by using the data generated by algorithms and mathematical calculations rather than real data, experience, and knowledge.

On the other hand, although it is possible to find many publications in aforementioned subjects, the number of publications that mention trade-off curves within product development context is very limited. For example, Kennedy et al. (2014) reported that the earliest use of trade-off curves in product development was by the Wright Brothers, who succeeded in the first manned and heavier-than-air flight in a very short time and with fewer budgets than their rivals in the late 1800s. It is believed that a part of this success was the use of trade-off curves in the early stages of product development. Sobek et al. (1999) reported that the use of trade-off curves has appeared at Toyota as a knowledge visualisation tool which facilitates the key tasks of set-based design. At Toyota “jidoka” refers to the visual management, a technique adapted from lean manufacturing to product development in order to simplify complex knowledge using visual tools such as trade-off curves (Morgan and Liker, 2006). They visually display subsystem knowledge in a graph so that engineers are able to explore the design space (Ward and Sobek II, 2014) and evaluate design alternatives (Kerga et al., 2014). Moreover, in a lean product development context, trade-off curves avoid the reinvention of previously considered design solutions during prototyping (Womack, 2006). Hence, engineers save time by not redesigning already existing solutions.

There are two main approaches to develop trade-off curves; these are math-based and knowledge-based which are presented in the following sub-section. Although aforementioned studies express that they use trade-off curves as a tool in product development processes, they do not provide a systematic approach of generating and using trade-off curves. Therefore, this paper presents a process to generate knowledge-based ToCs and use them for enabling SBCE activities as presented in section 4.

3.2. The characteristics of math-based trade-off curves

Math-based ToCs are generated by using the data output from simulating engineering applications by mathematical modelling (Browning and Eppinger, 2002; Fine et al., 2005; Panduro et al., 2006; Richards and Valavanis, 2010; Roemer and Ahmadi, 2004). Math-based ToCs have been used for different purposes: To visualise and compare conflicting design parameters (Li et al., 2013), and to support the decision making in multi-objective optimisation (Panduro et al., 2006). However, the ToC data in these studies is generated in a mathematical manner (e.g. simulations, algorithms, and mathematical programming) depending on assumptions (Malak and Paredis, 2010) rather than facts and knowledge. Hence, assumptions might be overestimated or underestimated which may lead designers to make an inaccurate decision. Moreover, due to the fact that uncertainty is an issue with these math-based ToCs based on assumption (Bitran and Morabito, 1999), there are thus risks and estimation errors (Roemer and Ahmedi, 2004). Additionally, the math-based ToCs might not be reused for future projects and they should be generated for every single project since different projects have different assumptions and constraints (Fine et al., 2005). Furthermore, while they are capable of generating thousands of solutions (Panduro et al., 2005), it might take time to compare and evaluate these solutions. Therefore, math-based trade-off curves do not provide the right environment to enable SBCE which requires accuracy of data, the right reusable knowledge environment and more focussed data. Therefore, the authors of this paper are focusing on knowledge-based ToCs, which are presented in the following subsection.

3.3. The characteristics of knowledge-based trade-off curves

Knowledge-based ToCs are generated by using the data based on facts and knowledge obtained from material providers, previous projects (including failed or incomplete projects), R&D, prototyping and testing. Therefore, knowledge-based ToCs usually display the real experiences from engineering activities or the knowledge that the companies already have.

The challenge is to provide knowledge in order to support key SBCE activities (see section 4): The generation of a set of conceptual designs, communicating sets to others, comparing alternative design solutions, trade-off and narrowing down the set of design solutions, and supporting the generation of the final optimum design solution (Correia et al., 2014; Kennedy et al., 2014; Khan et al., 2013; Oosterwal, 2010; Sobek et al., 1999; Ward and Sobek II, 2014). Thus, this research is concerned about how these SBCE activities could be enabled via the use of ToCs to provide the right knowledge environment. The characteristics of such environment are as following:

Visual: Data to be used during the early design stage should be in a visual form so that the designers would be able to quickly understand the trends among the design parameters (Correia et al., 2014; Levandowski et al., 2014; Maksimovic et al., 2012).

Easy to communicate: Captured knowledge should be clearly understood and communicated between different departments in the company (Al-Ashaab et al., 2013; Correia et al., 2014; Hong et al., 2004; Ward and Sobek II, 2014).

Data type: Design parameter data should be real and based on facts and knowledge rather than algorithms and mathematical formulas (Kennedy et al., 2014; Maksimovic et al., 2012; Sobek et al., 1999).

Minimum uncertainty: The uncertainty during the early design stage should be decreased to a minimum level for the designers to make precise decisions. This could be possible by using real data and experience rather than generating data with algorithms (Hong et al., 2004; Kennedy et al., 2014; Ward and Sobek II, 2014).

The amount of generated conceptual design solutions: Generating high amounts of design solutions (e.g. thousands) will take time to evaluate the sets and eliminate bad solutions (Al-Ashaab et al., 2013; Khan et al., 2013).

Reusable: Created usable knowledge during the early design stage should be stored rather than discarded in order to reuse it for future projects. Thus, the designers will save time by not generating the same design solutions repeatedly (Kennedy et al., 2014; Maksimovic et al., 2012).

It is worth to clarify that there are also studies named "fuzzy set-based tradeoffs" (Hernández-Luna et al., 2010 and Wang and Terpenny, 2003) which might cause confusion with set-based concurrent engineering. Zadeh (1965), who introduced the "fuzzy set theory", described it as a class of objects with a range of grades of characteristics (e.g. a set that includes not only black and white but also all the possible tones of grey). Thus, if the relationships between conflicting objectives are built based on this theory, it is called as fuzzy set-based tradeoffs. Fuzzy sets have been found as a new way to solve the problems that were not addressed previously by the standard multi-objective optimisation methods (for more information see Hernández-Luna et al., 2010; Wang and Terpenny, 2003 and Zadeh, 1965). It can be understood that fuzzy set-based tradeoffs are not SBCE, therefore, they are outside the context of this paper.

On the other hand, knowledge-based ToCs could represent the design limit by separating the feasible design area from the infeasible design area (Araci et al., 2016; Ward and S obek II, 2014). Thus, designers will be able to locate the point they want on these ToCs (Ward and Sobek II, 2014). Furthermore, since the history of the product does not change and some knowledge-based ToCs use historical data, designers can reuse these ToCs for the next projects (Levandowski et al., 2014). However, they should be updated carefully to include new technologies; hence innovation can be achieved in new projects.

3.4.1. Trade-off Curves within the Lean Product Development Concept

Customers demand innovative products more than ever before. Whoever introduces the innovative products to the market faster, they achieve the competitive advantage. In order to reduce the time-to-market, companies invest significant effort on their new product development activities. Lean product development (LeanPD) has been considered as an effective and efficient approach to new product development in terms of developing innovative products with high quality. In fact, Radeka (2012), in her book, explained the successful achievements of LeanPD implementations together with real industrial case studies.

Implementation of LeanPD requires a holistic approach that will guide organizations through the whole product life cycle (Al-Ashaab et al., 2013; Gremyr and Fouquet, 2012). This approach should clearly describe the lean principles and a systematic process for creating value, providing accurate knowledge, supporting continuous improvement and collaboration, and stimulating innovation (Silvério et al., 2020). To address these elements, set-based concurrent engineering (SBCE) process model has been developed (Khan et al., 2013). Associated lean tools and methods should also be well defined. Trade-off curves are one of these lean tools that are critical to lean product development, especially, to create knowledge (Ward, 2014).

Right knowledge environment is an inevitable element of lean product development (Araci et al., 2020; Canonico et al., 2020). Some researchers use SECI model (Socialisation, Externalisation, Combination, Internalisation) which is a theoretical framework for practices in creating knowledge (Canonico et al., 2020). Nonaka and Takeuchi (1995) proposed this framework to explain the secret of Japanese automobile producers in innovating dynamically and securing their competitive advantage. According to SECI, Externalisation element means transferring tacit knowledge (knowledge that is not documented) into explicit knowledge (documented and tangible). Ideally, organizations should keep their knowledge documented so that everyone can access and reuse. Internalisation element converts explicit knowledge to tacit knowledge which means that individuals can enhance their knowledge. Trade-off curves have the ability of converting different form of knowledge for a better use of the stakeholders of lean product development such as designers, customers, managers, suppliers, etc. By extracting data from previous projects and experience, trade-off curves play a role in externalisation. By visualising the conflicting relationships between the design parameters, ToCs can become a communication tool for internalisation among the stakeholders.

3.4.2. The Role of Trade-off Curves within Set-Based Concurrent Engineering Process Model

SBCE is a product development process within which products are developed by breaking them down into subsystems and designing sets of solutions for these subsystems in parallel. Sets of design solutions are narrowed down gradually by testing and communicating with other participants until the final solution is obtained (Al-Ashaab et al, 2013; Raudberget, 2010; Sobek et al., 1999; Ward et al, 1995). The SBCE process model that is used in this paper consists of five key phases: value research, map design space, concept set development, concept convergence, and detailed design (Al-Ashaab et al, 2013; Khan, 2012). Figure 2 illustrates the activity view of the SBCE process model that is used in this paper in order to demonstrate the use of generated physics-based ToCs.

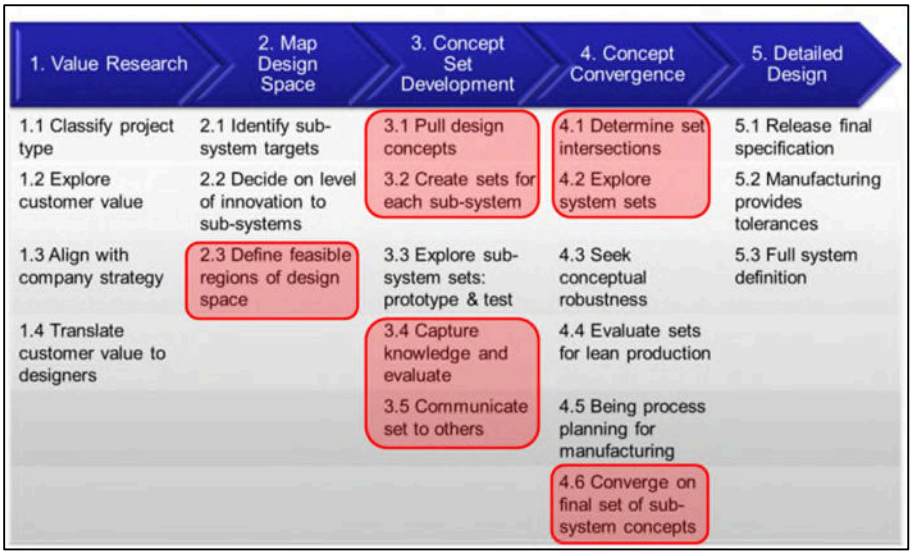


Figure 2 SBCE process model activity view (Khan, 2012)

Although there is no clear explanation of how to use ToCs in SBCE applications, the current literature review shows that ToC has a potential to enable some activities within the phases mentioned above. These activities are:

1. Identifying the feasible design solutions area (Khan et al., 2013; Maksimovic et al, 2012; Kennedy et al., 2014; Kerga et al., 2014).

2. Generating a set of conceptual designs (Oosterwal, 2010; Ward and Sobek II, 2014; Zehra et al 2020).

3. Communicating a set of designs to others (Correia et al., 2014; Levandowski et al., 2013).

4. Comparing alternative design solutions (Raudberget et al., 2010; Sobek et al., 1999).

5. Trade-off and narrow down the set of design solutions (Khan et al., 2013; Raudberget et al., 2010; Sobek et al., 1999).

During the SBCE process, designers intentionally postpone critical design decisions until the last possible moment in order to ensure a full understanding of customer requirements that are met by the final design solution (Al-Ashaab et al, 2013). However, communication, evaluation and learning effectively from several alternative designs can be challenging (Morgan and Liker, 2006). ToC is a powerful tool to address these challenges. Obtained information from the literature showed that ToCs could be used in the highlighted activities of the SBCE process model as illustrated in Figure 2. Suwanda et al. (2020) develop a software demonstrator of knowledge-shelf that capture design rationale in a structured manner to enable effective application of SBCE where ToC is used to visualise knowledge and narrowing down the design set.

4. The Process of Generating and Using Physics-based Trade-Off Curves for a "VR-Card Reader"

This section presents a process of generating trade-off curves based on the understanding physics of the product in conceptual stage. In this stage the generated physics-based ToCs are used to enable key SBCE activities after

developing a set of design solutions as well as supporting the product development (PD) team for decision-making and communication between the departments. The key SBCE activities are; comparing between the alternative design solutions and narrowing down the design set. Each step of the process of using ToCs in enabling SBCE has been explained in detail in the following paragraphs.

Steps	Activities
1. Understand the First Design Set	1.1. Use the developed set of design solutions from SBCE process 1.2. Use the identified customer requirements and decision criteria
2. Understand Physiscs of the Product	2.1. Study the physical characteristics/features of the product under development 2.2. Identify new design parameters to generate physics-based ToCs 2.3. Evaluate the relations between the design parameters 2.4. Generate non-scale ToCs based on the obtained physics knowledge
3. Test and Analyse	3.1. Turn non-scale ToCs into scaled ToCs based on physics knowledge 3.2. Identify feasible area and/or an optimum point in the physics-based ToCs associated with the specific design parameter
4. Compare the Solutions of the Design Set	4.1. Represent the data of the selected design set on the generated physics-based ToCs 4.2. Communicate and compare the design solutions 4.3. Expand the feasible area if possible
5. Select / Narrow Down Designs	5.1. Select the design solutions in the feasible area or close to the identified optimum point 5.2. Second stage of narrowing down
6. Enhance Design	6.1. Explore the opportunities of creating a new improved design based on combining and/or modifying solutions from the selected designs 6.2. Capture and store the obtained knowledge

Figure 3 The process of using ToCs based on the understanding of physics to compare and narrow down the design set throughout the SBCE process

Step 1: Understand the First Design Set

1.1 Use the developed set of design solutions from SBCE process: The PD team should use and study the developed design set during the SBCE process. This set could be obtained from the designs that were developed by ToCs based on historical data, R&D department, simulations, and prototyping and testing (see Figure 6 as an example for a set of alternative design solutions).

1.2 Use the identified customer requirements and decision criteria: In order to achieve an optimum design solution which addresses the needs of the customer, the PD team should understand the identified customer requirements and decision criteria which are defined in Section 3. These customer requirements and decision criteria could be obtained by brainstorming among the PD team members.

Step 2: Understand Physics of the Product

Before comparing and narrowing down the alternative design solutions, it is essential to know and understand the purpose, function, and working environment of the product under development. This understanding will also be

enabled by the identified customer requirements and decision criteria. This is to generate a new set of ToCs based on understanding the physics of the product under consideration. The following tasks are recommended to be followed;

2.1 Study the physical characteristics/features of the product under development: Fundamental features and the physical characteristics of the product under development should be investigated by conducting a research based on physics laws (e.g. the relation between the density and weight). Required information could be obtained from the literature, industrial practices, and physics applications.

2.2. Identify new design parameters to generate physics-based ToCs: New design parameters should be identified based on the understanding physics of the product and identified customer requirements and decision criteria.

2.3. Evaluate the relations between the design parameters: Design parameters should be reviewed and understood in relation to the product physics that has been studied in activity 2.1. Thus, the designers will be more confident during decision-making on comparison between the alternative design solutions and narrow down the set by eliminating weak design solutions which are not meeting the requirements and criteria

2.4. Generate non-scale ToCs based on the obtained physics knowledge: The evaluation of the design parameters against the product physics will help to generate non-scale ToCs which is called as “physics-based ToCs”. Non-scale ToCs could be communicated easily with stakeholders even without requiring a detailed engineering background.

Step 3: Test and Analyse

Figure 4 illustrates the overall process of generating physics-based ToCs to compare and narrow down alternative design solutions throughout the SBCE process. In order to start generating ToCs related to the understanding physics of the product, the activities below are recommended to be followed;

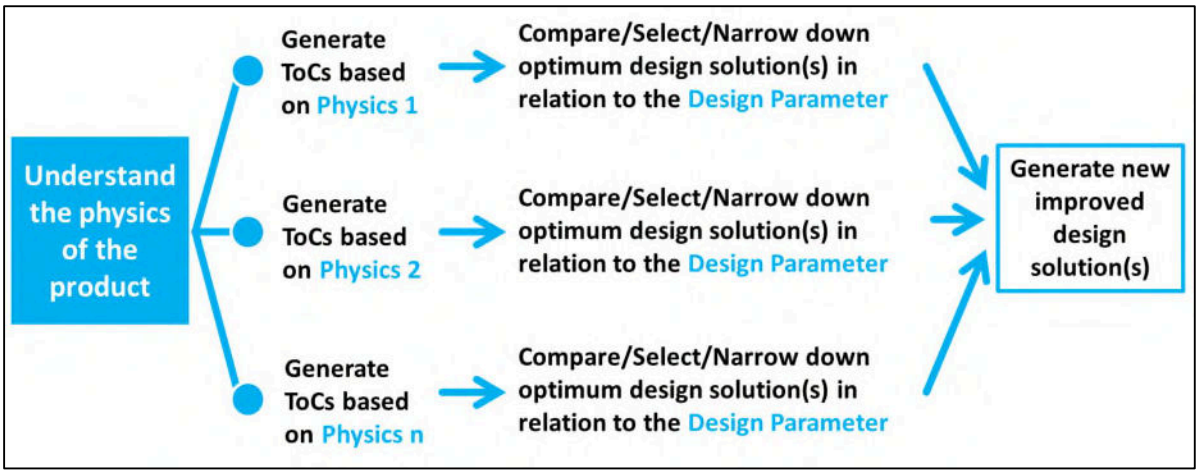


Figure 4 Overall representation of the process of generating physics-based ToCs to compare and narrow down alternative design solutions throughout the SBCE process

3.1. Turn non-scale ToCs into scaled ToCs based on physics knowledge: Real data should be collected in order to turn non-scale ToCs into scaled ToCs. The first data could be obtained from the specific design parameter and dimension of the individual solutions in the design set as well as from the certain simulation and testing.

3.2. Identify feasible area and/or an optimum point in the physics-based ToCs associated with the specific design parameter: PD team should study the effects of changing design parameters on the performance of the design. As result of understanding physics, designers could identify the optimum point in the physics-based ToCs associated with the specific design parameter and/or feasible area on each ToC that meets the customer requirements and decision criteria.

Step 4: Compare the Solutions of the Design Set

Comparison is needed to distinguish the good quality designs from the weak design solutions, hence, to achieve/obtain a robust final optimum solution. PD team will be able to see the differences and similarities between generated design solutions by using generated physics-based ToCs in Step 3 Test and Analyse. The following are the suggested activities to be able to compare the design set;

4.1. Represent the data of the selected design set on the generated physics-based ToCs: The values of the design parameter of each solution in the selected design set are plotted against the generated physics-based ToCs. Thus, the PD team will be able to see the differences between the physical features of the developed design solutions within the identified feasible solutions.

4.2. Communicate and compare the design solutions: The projection of the design parameter value of every solution in the physics-based ToCs will provide visualisation of each solution which helps to compare against the identified customer requirements and decision criteria. This will assist the design team to make a decision and narrow down solutions.

4.3. Expand the feasible area if possible: Due to the progress of the work and having a good understanding at this stage will help to expand the feasible area defined in activity 3.2. This will improve the design performance and innovation of the product under development. It is worth to mention that the feasible area expansion is not a parametric extension which means an equal expansion from all directions of the feasible area. Rather, it is going to be expanded case by case according to the project under consideration.

Step 5: Select and Narrow Down Designs

During the SBCE process, the PD team intends to trade-off and narrow down the set of design solutions. ToCs provide an objective manner to accomplish this task. Following activities are suggested for selecting and narrowing down;

5.1. Select the design solutions in the feasible area or close to the identified optimum point: The intention of this activity is to select good quality designs for further narrowing down throughout the SBCE process. Those design

solutions that fall in the feasible area should be selected. In addition, those designs that do not fall in the feasible area but meet the requirements and show satisfying performance should also be selected.

5.2. Second stage of narrowing down: This activity helps to further narrow-down the selected design solutions resulted from activity 5.1. This is to evaluate design solutions and to compare them to each other in order to obtain more optimised values of the design parameters identified in activity 2.2. From the selected design solutions, those design(s) should be eliminated that show weaker or lower performance than the desired optimum point. On the other hand, those design(s) should be selected for further development throughout the SBCE process that show better performance than the others and that meet the customer requirements and decision criteria. Hence, the PD team will be able to achieve further narrowing down of the design solutions.

Step 6: Enhance Design:

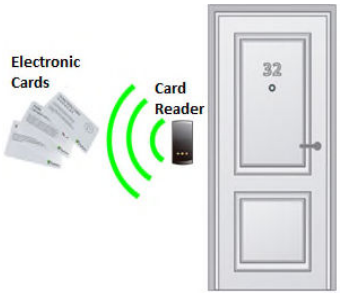
6.1. Explore the opportunities of creating a new improved design based on combining and/or modifying solutions from the selected designs: This activity is proposed in order to explore generating new enhanced design based on two or more selected solutions. This is to identify and select good complimentary features of the selected design solutions to generate new design.

6.2. Capture and store the obtained knowledge: Obtained knowledge should be kept for reuse in the future projects.

This proposed process is validated by an industrial case study of vandalism resistant card reader (VR-reader) based on a research project in the following section.

5. Industrial Case Study: Compare and narrow down the design-set based on understanding the physics of the product

This section presents the use of the process shown in Figure 3 to generate ToCs based on the understanding physics of the product and using these ToCs to enable the application of SBCE at an electronic access control system manufacturer. The specific product for this case study is commonly known as a “card reader” as shown in Figure 5 and it is an important part of an electronic access control system. The card reader works by identifying the different users trying to access the system and by sending this information to another device which verifies if the users are allowed to have access. Thus, the user company will be able to gather information about the entries into the system (e.g. the number of people accessing the system within a specific time period, also the number of people within the system for fire alarm reasons).



(a) Electronic access control system diagram



(b) The card reader
(the product under development)

Figure 5 The card reader within electronic access control system

The case scenario is to develop a card reader that is resistant to vandalism. Vandalism can be defined as deliberately damaging the product. Additional requirements to vandalism are the reliability and the cost of the product. This case study aims to present how to use physics-based ToCs within the following activities;

1. To support product development team's (PD team) decision-making throughout the SBCE process.

2. To enable SBCE process model key activities: Compare design solutions and Narrow down the design sets.

Step 1: Understand the First Design Set

1.1 Use the developed set of design solutions from SBCE process: The design set to be presented in this case study was produced by the participation of the author throughout a project in 2014. Further information about the development of the design set could be found in the following source: Set-Based Concurrent Engineering Application: A Detailed Case Study (Garcia Almeida, 2014)

Figure 6 illustrates the set of design solutions for the front cover of the card reader that is used in this case study. The set consists of 10 front cover. Since there is no change required in other components of the product, designs were created only for the front cover which is mostly affected by the vandal actions, for example, pouring water, hitting, and burning.

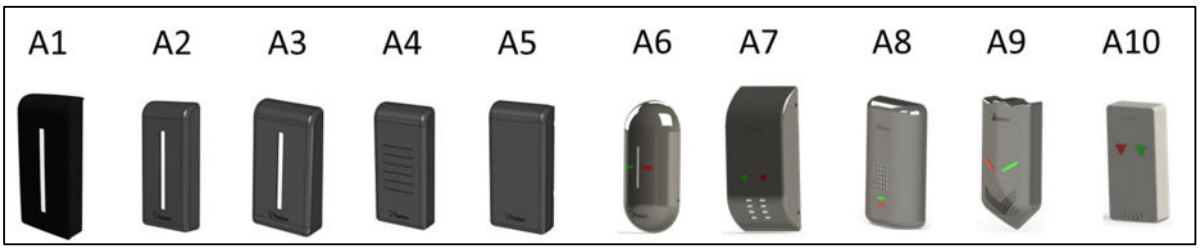


Figure 6 The set of alternative design solutions of the front cover of the access control system case study. In this specific example there are 10 design solutions.

1.2 Use the identified customer requirements and decision criteria: The following customer requirements have been identified by examining the customer feedback of the current product of the company as well as by brainstorming and interacting with the design team:

1. 250,000 activations during the product life (5 years): The card reader must work for a minimum of 250,000 times within five years.

2. Minimum operational distance of 10 mm: The card reader must be activated by the electronic cards at a minimum of 10mm distance.

3. Maximum operational distance of 50 mm: The card reader must be activated by the electronic cards at a maximum of 50mm distance.

4. The card reader's price must not exceed the market price.

The following decision criteria have been identified by analysing the customer requirements, brainstorming with the design team and also by using the Analytical Hierarchy Process (AHP) method (Bhushan and Rai, 2004) which is not presented here as it is outside of the scope of this paper. Each criteria has been weighed according to their importance from the company point of view:

1. Security and protection (49%): The new card reader should be protected against vandalism, violation, burning, and breaking.

2. Reliability (35%): The new card reader should work properly all the time at least during the product life as identified in the customer requirements.

3. Cost (16%): The product cost of the new card reader should be around 20% of the retail price which itself should be less than the expected market price.

For further presentation of the case study, customer requirements and decision criteria will be called as "key value attributes (KVA)" in the following activities.

Step 2: Understand Physics of the Product

2.1 Study the physical characteristics/features of the product under development: The physic characteristics have been studied to understand the parameters that could affect the product features. The knowledge of the KVA (security and protection, reliability and cost effectiveness) facilitated identifying the design parameters. Figure 7 illustrates the identified design parameters as result of understanding the physics of the card reader.

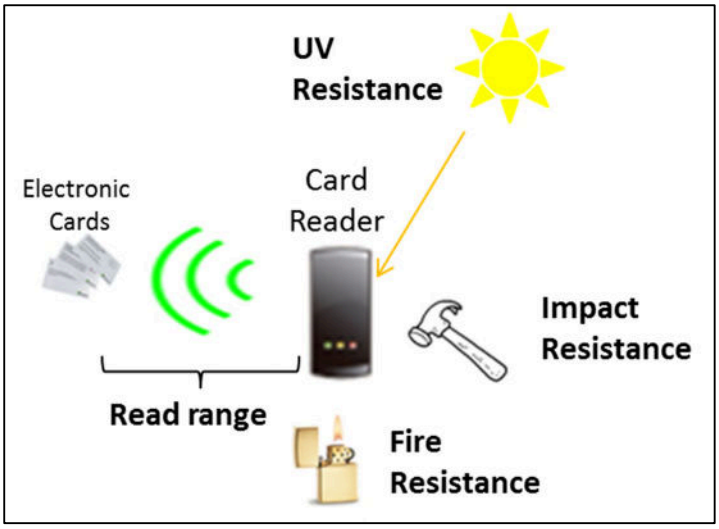


Figure 7 Illustration of the design parameters identified by the understanding physics of the product

These design parameters were identified as;

Security and protection related design parameters;

- UV resistance: Product may crack or deform if it is not durable against the UV lights when it is exposed to sunlight. Therefore, all the external elements of the reader must be UV resistant and suitable for environments with long time exposition to the sun light.
- Fire resistance: Product might be damaged when it is exposed to fire. The concept of the fire in this case study is trying to burn the product by using a lighter.
- Impact resistance: Product might be cracked or damaged by hitting, punching or kicking.

Reliability related design parameters;

- Read range: Read range is measured as the distance of the magnetic area created by the reader's module (see Figure 7). Thus, once the electronic card reaches this read range, the electronic access system is activated by receiving the radio signals.

Cost effectiveness related design parameters;

- Cost: Product cost is affected depending on the amount of the material used.

2.2. Identify new design parameters to generate physics-based ToCs: Obtained physics knowledge in activity 2.1 helped to identify new design parameters. As it could be seen in Figure 8, it was found that wall thickness, depth and geometry of the front cover have effects on the UV resistance, fire resistance, impact resistance, read range and cost. Changing the numeric values of wall thickness and depth affects the performance of the design solution. Similarly, different front cover geometries, as some of the possible shapes shown in Figure 8, affect the identified design parameters in activity 2.1. Relations between these design parameters are presented in the next activity.

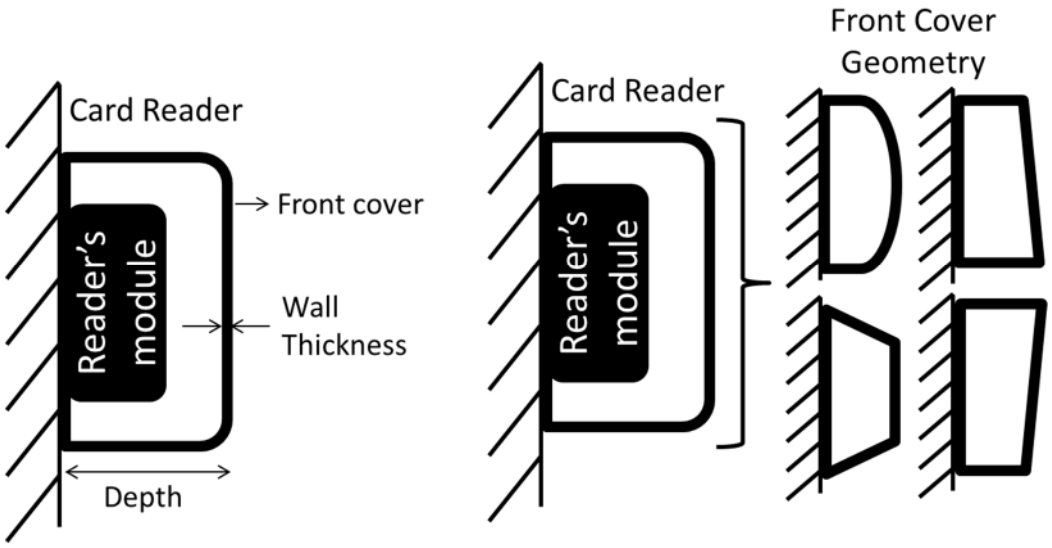


Figure 8 Illustration of the identified new design parameters (wall thickness, depth, front cover geometry) using the knowledge of physics of the product investigated in activity 2.1

2.3. Evaluate the relations between the design parameters: Information has been captured and presented as following:

UV resistance: Increasing wall thickness and depth will increase the UV resistance. Because the thicker and wider front cover protects the product from the sun lights to reach inside and affect the functionality of the reader's module (see Figure 7 and Figure 8). In addition, the geometry of the front cover could protect the product by reflecting the UV lights.

Fire resistance: Increasing wall thickness and depth will increase the fire resistance. Because a front cover with thicker wall thickness and wider depth delays the flame to damage the product and reach the reader's module which means a positive effect regarding the security and protection and reliability of the product.

Impact resistance: Increasing wall thickness and depth will increase the impact resistance. Because the thicker and wider front cover protects the product from being damaged easily by hitting, kicking or punching. Moreover, different angles of the front cover geometry will protect the product against the vandalism actions better than a flat geometry.

Read range: Increasing wall thickness and depth will affect the read range in a negative way. As it could be seen in Figure 7, if the wall thickness and the depth of the front cover increase, this will cause decrease in the read range as the distance between the reader's module and the surface of the front cover increases.

Cost: A design solution with thicker and wider front cover will require more material which leads to cost increase.

2.4. Generate non-scale ToCs based on the obtained physics knowledge: Activity 2.3 helped the authors to generate non-scale ToCs in order to see the relationships and interactions between the design parameters in a single diagram (see Figure 9. This case study focused on the relationships of the UV resistance, fire resistance, impact resistance, read range and cost with wall thickness only.

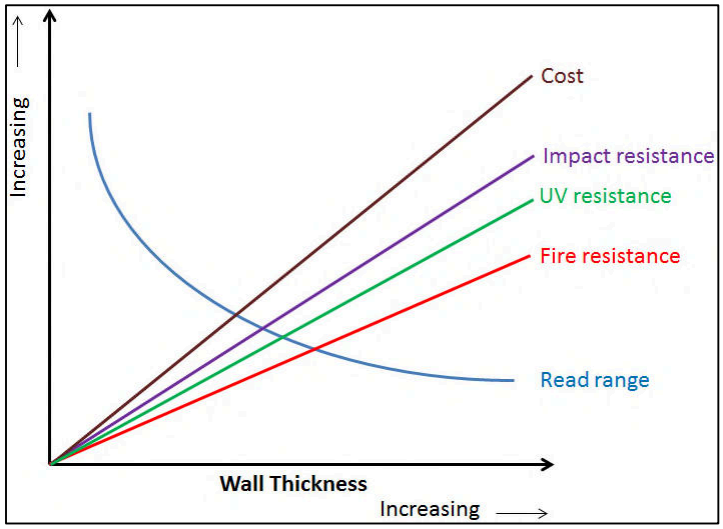


Figure 9 The non-scale ToC illustrating the relationships between wall thickness and the design parameters: UV resistance, fire resistance, impact, resistance, read range, and cost

As depicted in Figure 9, increasing the wall thickness of the front cover will improve the resistance to impact and fire. However, these enhancements come at the expense of rising device cost due to increased material requirements. Furthermore, the read range of the device will decrease as a thicker wall will weaken radio signals passing through the product.

Step 3: Test and Analyse

3.1. Turn non-scale ToCs into scaled ToCs based on physics knowledge: As it could be understood from the step 2, wall thickness and depth have significant effects on the identified design parameters. Due to the limited amount of data available, in this case study, only impact and fire resistance of the designs will be analysed via structural and thermal simulations. Structural analyses were focused on simulating the impact of a hammer, while thermal analyses were focused on simulating the action of a lighter flame. Ansys software was used for simulations. The input parameters of the simulations are shown in Table 1.

Table 1 Structural and thermal analyses inputs

Input Parameters	Input Values
Applied temperature	1400°C
Area of hammer	0.000314 m^2
Mass of hammer + arm	7.4 kg
Approx. velocity of hammer coming down	5 m/s
Estimated bounce back	1m/s
Impact time	0.01s
Acceleration (V1-V2)/t	600m/s^2
Force	4500N

In order to turn non-scale ToCs into scaled physics-based ToCs, following indicators were used as result of the structural and thermal analyses;

Indicators for structural analysis:

- Highest stress level (mPa) (related to the impact resistance)
- Deformation scale (related to the impact resistance)

Indicators for thermal analysis:

- Highest temperature level (^{o}C) (related to the fire resistance)

Figure 10 illustrates the physics-based ToCs that were generated according to the knowledge from the non-scale ToCs identified in activity 2.4.

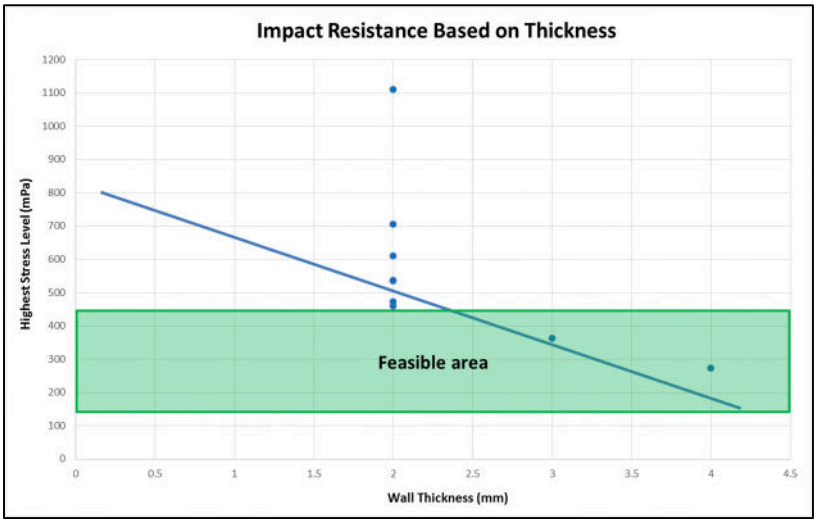
3.2. Identify feasible area and/or an optimum point in the physics-based ToCs associated with the specific design parameter: Optimum point for thermal analysis was considered as a melting point of 230^{o}C which had an impact on the surface of the front cover accepted to be flame retardant. Therefore, the performance of the design solution should be higher than 230^{o}C. Regarding the impact resistance, designs were expected to be durable at least up to 450Mpa which is a value that could be considered as a vandal action. In addition, the lower deformation scale will provide a better impact resistance. Feasible areas for each ToCs are identified according to these targets (highest temperature level ≥ 230^{o}C and highest stress level ≤ 450mPa) and illustrated in Figure 10

Step 4: Compare the Solutions of the Design Set

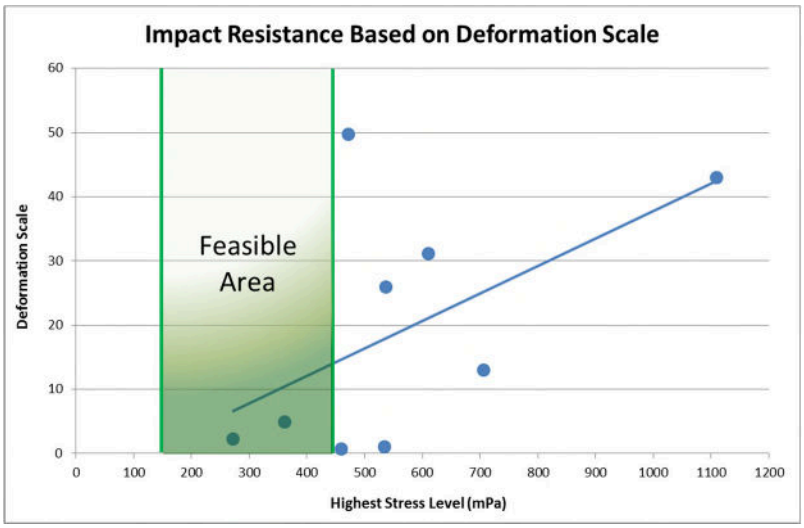
4.2. Represent the data of the selected design set on the generated physics-based ToCs: Data was collected from the structural and thermal simulations and presented in Table 2. This data was plotted against the generated physics-based ToCs as shown in Figure 10. Front cover design A1 has been excluded from the design set as it is the original design that requires improvement.

Table 2 Collected data of values of the design parameters of each front cover design.

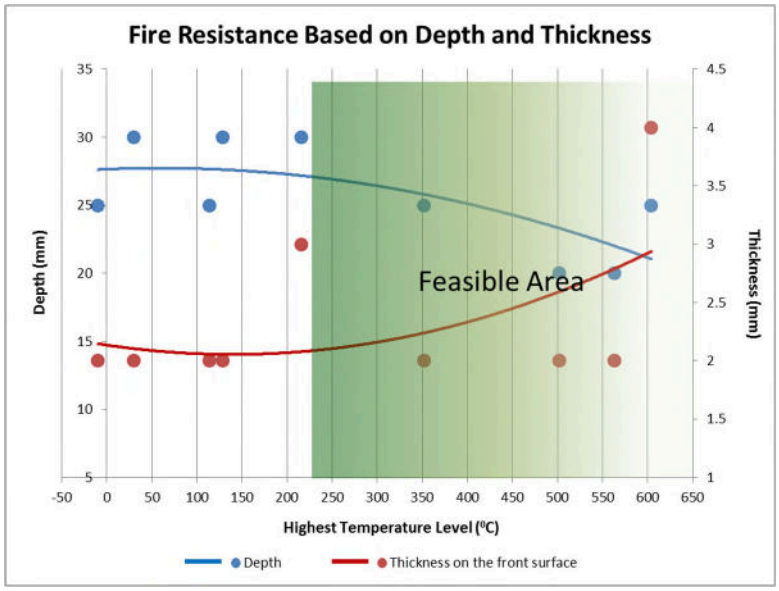
Design Solution Number	Front Cover Thickness (mm)	Depth (mm)	Highest Stress Level (mPa)	Highest Temp. Level (^{o}C)	Deformation Scale
A2	2	20	460	502	0.72
A3	2	25	706	352.05	12.95
A4	2	20	534	563.05	1
A5	4	25	272	604.05	2.29
A6	2	30	1110	29.65	42.97
A7	2	25	610	-9.95	31.13
A8	2	30	472	128.95	49.71
A9	3	30	362	216.05	4.9
A10	2	25	537	114.25	25.92



(a)



(b)



(c)

Figure 10 Physics-based ToCs obtained from non-scale ToCs related to the impact and fire resistance performance of the product

4.3. Communicate and compare the design solutions: It was found that there are two design solutions fall into the feasible area in Figure 10-a and Figure 10-b while there are four design solutions in the feasible area of Figure 10c.

4.4. Expand the feasible area if possible: As it could be seen in Figure 10-a and Figure 10-b, if the design team sets the target for highest stress level as 500mPa rather than 450mPa, two more design solutions will be covered in the feasible area.

Step 5: Select and Narrow Down Designs

5.1. Select the design solutions in feasible area or close to the identified optimum point: Design solutions, shown in Figure 6, within the expanded feasible area are selected and listed as following according to the related physics-based ToCs as shown in Figure 10;

A2, A5, A8, A9 → Impact resistance based on thickness (Figure 10-a)

A2, A5, A8, A9 → Impact resistance based on deformation scale (Figure 10-b)

A2, A3, A4, A5 → Fire resistance based on depth and wall thickness (Figure 10-c)

Selected design solutions set consists of 6 different designs (A2, A3, A4, A5, A8, A9) to be used for the second stage of narrowing down.

5.2. Second stage of narrowing down: Selected design solutions were evaluated and the results have been presented as follows:

- A2 and A5 are selected because they meet requirements for both the impact and fire resistance.
- A3 and A4 are eliminated because, although they meet the requirement for fire resistance, they are not resistant against the impact applied during the structural analysis.
- A8 is eliminated because the deformation scale of this design (49.71) is very high compared to other design solutions. Moreover, the melting point is 128.95 which is much lower than the identified melting point 230^{o}C.
- A9 is selected because the values of the design parameters show a promising performance to be considered for design enhancement in the following activity 6.1.

As result, there are three design solutions selected (front covers: A2, A5, and A9) for further development of the final optimum design solution.

Step 6: Enhance Design:

Due to being out of scope of this paper, this step is considered as a future work. However, it could be suggested that A9 in Figure 11 could be considered to be enhanced since the design parameters values show a promising performance in order to meet requirements for the impact resistance and fire resistance.

6. Discussion and Conclusions

This case study presented that physics-based ToCs could be used as a communication and decision support tool while they enable the key SBCE activities: comparing alternative design solutions and narrowing down the design set. Used design set in this case study consisted of 10 component design solutions. In order to compare and narrow down this design set, three ToCs were generated by using the physics knowledge of the product as explained in Step 1 in Section 5. Generated physics-based ToCs facilitated communication with the stakeholders by creating and visualising a knowledge environment. As result of comparing the alternative design solutions six designs were selected for the second stage of narrowing-down. These design solutions are front covers A2, A3, A4, A5, A8, and A9 as shown in Figure 11 - C. After that, the authors compared these selected designs to each other in order to select the solutions that showed better performance than the others. Therefore, designs A2, A5 and A9 are selected for further development of the final optimum design solution (see Figure 11 - D). It could be said that the knowledge stored in ToCs could be reused in future projects; hence the discarding knowledge would be prevented which is considered as a main contribution of this paper.

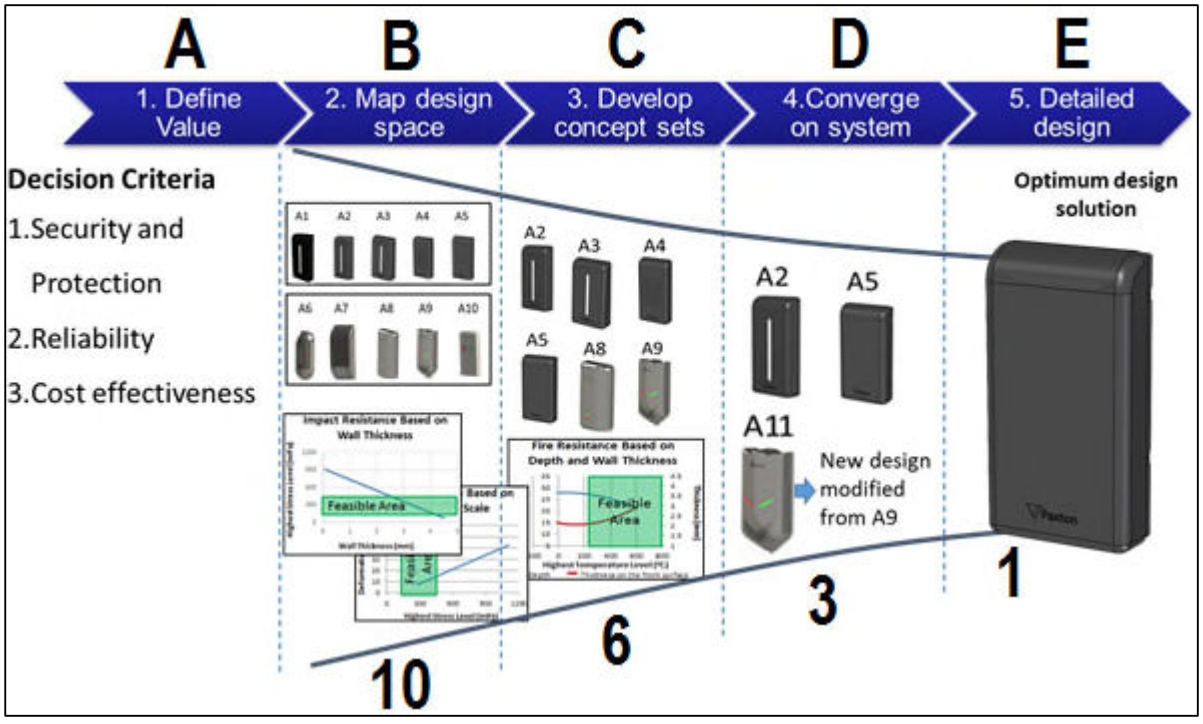


Figure 11 Overall view of the case study within the SBCE process model by the use of physics-based ToCs

To conclude, it could be said that physics-based ToCs are useful and effective tools to enable key set-based concurrent engineering activities. As a core enabler of the lean product development approach, SBCE requires the right knowledge environment in quick and visual manner which has been addressed by demonstrating physics-

knowledge in trade-off curves (ToCs). Therefore, a systematic process has been developed and presented in this paper. The research found that physics-based ToCs could help to identify different physics-characteristics of the product in the form of design parameters and visualise in a single graph in order for all stakeholders to understand without a need for an extensive engineering background. In addition, these ToCs enable two key activities of SBCE process model: Comparing design solutions and narrowing down the design sets. Hence, designers could save time by obtaining accurate knowledge via the use of physics-based ToCs during their product development activities. This paper demonstrated this fact by applying a case study which aims to develop a new electronic access card-reader that is resistant to vandalism. As a tangible result, it has been understood that ToCs provided not only an accurate and visual form of knowledge environment but also supported the communication and decision-making within the product development team to achieve an innovative robust design.

Authors expect that this paper will guide companies which are implementing set-based concurrent engineering processes throughout their lean product development journey. Physics-based trade-off curves will facilitate accurate decision-making in comparing and narrowing down the design-set through the provision of right knowledge environment.

References

Abido, M.A. (2003) "A novel multiobjective evolutionary algorithm for environmental/economic power dispatch," *Electric Power Systems Research*, 65(1), pp. 71–81.

Al-Ashaab, A., Golob, M., Attia, U.M., Khan, M., Parsons, J., Andino, A., Perez, A., Guzman, P., Onecha, A. and Kesavamoorthy, S. (2013) "The transformation of product development process into lean environment using set-based concurrent engineering: A case study from an aerospace industry," *Concurrent Engineering Research and Applications*, 21(4), pp. 268–285.

Araci, Z.C., Al-Ashaab, A., Maksimovic, M. (2016), "Knowledge Creation and Visualisation by Using Trade-off Curves to Enable Set-based Concurrent Engineering", *Electronic Journal of Knowledge Management,* v.14 (1), p. 75-88.

Araci, Z.C (2017) Knowledge creatıon and vısualısatıon by usıng trade-off curves to enable set-based concurrent engıneerıng applicatıons. PhD thesis. Manufacturng Department, Cranfield University, Cranfield. UK.

Araci, Z.C., Tariq M.U., Al-Ashaab, Braasch J.H. and Simsekler E (2020) Creating Knowledge Environment during Lean Product Development Process of Jet Engine. International Journal of Advanced Computer Science and Applications, Vol. 11, No. 5, 2020, pages 58-62.

Askar, S. and Tiwari, A. (2011) "Finding Innovative Design Principles for Multiobjective Optimization Problems," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 41(4), pp. 554–559.

Avigad, G. and Moshaiov, A. (2010) "Set-based concept selection in multi-objective problems involving delayed decisions," *Journal of Engineering Design*, 21(6), pp. 619–646.

Bhushan, N. and Rai, K. (2004) Strategic Decision Making: Applying the Analytic Hierarchy Process. 2004 edition. Springer, London. ISBN 978-1-85233-864-0.

Bitran, G.R. and Morabito, R. (1999) “An overview of tradeoff curves in manufacturing systems design,” *Production and operations management*, 8(1), pp. 56–75.

Bretthauer, K.M., Shetty, B. and Syam, S. (2003) “A specially structured nonlinear integer resource allocation problem,” *Naval Research Logistics*, 50(7), pp. 770–792.

Browning, T.R. and Eppinger, S.D. (2002) “Modeling impacts of process architecture on cost and schedule risk in product development,” *IEEE Transactions on Engineering Management*, 49(4), pp. 428–442.

Burke, W.J., Merrill, H.M., Schweppe, F.C., Lovell, B.E., McCoy, M.F. and Monohon, S.A. (1988) “Trade off methods in system planning,” *Power Systems, IEEE Transactions on*, 3(3), pp. 1284–1290.

Canonico, P., De Nito, E., Esposito, V., Iacono, M. P. and Consiglio, S. (2020) “Knowledge creation in the automotive industry: Analysing obeya-oriented practices using the SECI model”, *Journal of Business Research*, 112 (2020), pp. 450-457.

Cao, Y. and Yang, Z. (2004) “Multiobjective process controllability analysis,” *Computers & Chemical Engineering*, 28(1-2), pp. 83–90.

Catalão, J.P.S., Mariano, S.J.P.S., Mendes, V.M.F. and Ferreira, L.A.F.M. (2008) “Short-term scheduling of thermal units: emission constraints and trade-off curves,” *European Transactions on Electrical Power*, 18(1), pp. 1–14.

Correia, A.T., Stokic, D. and Faltus, S. (2014) “Mechanisms for communication and knowledge sharing for set-based concurrent engineering,” *International Journal of Product Development*, 19(5), pp. 328–347.

Dunning, P.D., Stanford, B.K., Kim, H.A. and Jutte, C. V. (2014) “Aeroelastic tailoring of a plate wing with functionally graded materials,” *Journal of Fluids and Structures*, 51 Academic Press, pp. 292–312.

Fine, C.H., Golany, B. and Naseraldin, H. (2005) “Modeling tradeoffs in three-dimensional concurrent engineering: a goal programming approach,” *Journal of Operations Management*, 23(3), pp. 389–403.

Garcia Almeida, C. (2014), *Set-based concurrent engineering application: a detailed case study,* Cranfield University, MSc Thesis.

Gardner, Jr. and Everette, S. (1990) “Evaluating forecast performance in an inventory control system,” *Management Science*, 36(4), pp. 490–499.

Gremyr, I. and Fouquet, J. (2012) “Design for six sigma and lean product development,” *International Journal of Lean Six Sigma*, 3(1), pp. 45-58.

Grewal, C.S., Enns, S.T. and Rogers, P. (2014) “Measuring the performance sensitivity of replenishment systems using tradeoff curves,” *European J. of Industrial Engineering*, 8(5) Inderscience Enterprises Ltd., p. 646.

Hernández-Luna, A.A., Moreno-Grandas, D.P. and Wood, K.L. (2010) “Trade-off of fuzzy set-based design parameters,” *IIE Annual Conference and Expo 2010 Proceedings*. Institute of Industrial Engineers.

Holtzman, J.M. (1984) “Automatic Speech Recognition Error/No Decision Tradeoff Curves,” *IEEE Transactions on Acoustics, Speech, and Signal Processing*, ASSP-32(6), pp. 1232–1235.

Hong, P., Nahm, A.Y. and Doll, W.J. (2004) “The role of project target clarity in an uncertain project environment,” *International Journal of Operations & Production Management*, 24(12), pp. 1269–1291.

Kennedy, B.M., Sobek II, D.K. and Kennedy, M.N. (2014) “Reducing rework by applying set-based practices early in the systems engineering process,” *Systems Engineering*, 17(3), pp. 278–296.

Kerga, E., Taisch, M., Terzi, S., Bessega, W., and Rosso, A. (2014) “Set-based concurrent engineering innovation roadmap (SBCE IR): a case on Adiabatic Humidification,” *International Journal of Design Creativity and Innovation*, 2(4).

Khan, M.S. (2012) *The construction of a model for Lean Product Development*. Cranfield University, PhD Thesis.

Khan, M.S., Al-Ashaab, A., Shehab, E., Haque, B., Ewers, P., Sorli, M. and Sopelana, A. (2013) “Towards lean product and process development,” *International Journal of Computer Integrated Manufacturing*, 26(12), pp. 1105–1116.

Kuo, C.-L., Su, C.-P.J., Chu, C.-H. and Miao, H.-Y. (2014) “A statistical framework for characterizing the nanotube buckypaper manufacturing process,” *International Journal of Precision Engineering and Manufacturing*, 15(8), pp. 1601–1608.

Levandowski, C., Michaelis, M.T. and Johannesson, H. (2014) “Set-based development using an integrated product and manufacturing system platform,” *Concurrent Engineering Research and Applications*, 22(3), pp. 234–252.

Li, Y.Z.; Sheng, M.; Yang, C.G.; Wang, X.J. (2013) “Energy efficiency and spectral efficiency tradeoff in interference-limited wireless networks,” *IEEE COMMUNICATIONS LETTERS*, 17(10), pp. 1924–1927.

Liker, J.K. and Morgan, J. (2011) “Lean product development as a system: A case study of body and stamping development at Ford,” *Engineering Management Journal*, 23(1), pp. 16-28.

Maksimovic, M., Al-Ashaab, A., Sulowski, R. and Shehab, E. (2012) “Knowledge visualization in product development using trade-off curves,” *IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 708–711.

Malak, R.J. and Paredis, C.J.J. (2010) “Using Parameterized Pareto Sets to Model Design Concepts,” *Journal of Mechanical Design*, 132(4).

Mohagheghi, M., Kapat, J. and Nagaiah, N. (2014) “Pareto-Based Multi-Objective Optimization of Recuperated S-CO 2 Brayton Cycles,” *Volume 3B: Oil and Gas Applications; Organic Rankine Cycle Power Systems; Supercritical CO2 Power Cycles; Wind Energy*. ASME, Vol.3B.

Morgan, J.M. and Liker, J.K. (2006) *The Toyota product development system: integrating people, process, and technology*. New York: Productivity Press. ISBN 1563272822.

Oosterwal, D.P. (2010) *The lean machine: how Harley-Davidson drove top-line growth and profitability with revolutionary lean product development*. New York: AMACOM American Management Association. ISBN 9780814413784.

Otto, K.N. and Antonsson, E.K. (1991) “Trade-off strategies in engineering design,” *Research in Engineering Design*, 3(2), pp. 87–103.

Quirante, T., Sebastian, P. and Ledoux, Y. (2013) “A trade-off function to tackle robust design problems in engineering,” *Journal of Engineering Design*, 24(1), pp. 64–81.

Panduro, M.A., Brizuela, C.A., Covarrubias, D. and Lopez, C. (2006) “A trade-off curve computation for linear antenna arrays using an evolutionary multi-objective approach,” *Soft Computing*, 10(2), pp. 125–131.

Pershing, B. (1968) “Dragster Aerodynamics, Streamlining versus Weight,” *Aerodynamics of Sports and Competition Automobiles, Proc of the AIAA Symp; Los Angeles, CA, USA*., pp. 39–51.

Preetha Roselyn, J., Devaraj, D. and Dash, S.S. (2014) “Multi-Objective Genetic Algorithm for voltage stability enhancement using rescheduling and FACTS devices,” *Ain Shams Engineering Journal*, 5(3), pp. 789–801.

Radeka, K. (2013). *The mastery of innovation: a field guide to lean product development*. CRC Press, Taylor & Francis Group.

Raudberget, D. (2010) “Practical applications of set-based concurrent engineering in industry,” *Strojniski Vestnik/Journal of Mechanical Engineering*, 56(11), pp. 685–695.

Rhyu, J.H., and Clearance and Kwak, B.M. (1988) “Optimal stochastic design of four-bar mechanisms for tolerance and clearance,” *Journal of mechanisms, transmissions, and automation in design*, 110(3), pp. 255–262.

Richards, Z.D. and Valavanis, K. (2010) “Particle Swarm trade-off curve analysis for bi-objective optimization,” *IEEE Congress on Evolutionary Computation, CEC 2010*. Barcelona, Spain, pp. 1–6.

Ringen, G., & Holtskog, H. (2013). How enablers for lean product development motivate engineers. International Journal of Computer Integrated Manufacturing, 26(12), 1117–1127.

Roemer, T.A. and Ahmadi, R. (2004) “Concurrent crashing and overlapping in product development,” *Operations research*, 52(4), pp. 606–622.

Samarasinghe, T., Inaltekin, H. and Evans, J.S. (2013) “The feedback-capacity tradeoff for opportunistic beamforming under optimal user selection,” *Performance Evaluation*, 70(7-8), pp. 472–492.

Silvério, L., Trabasso, L.G. and Pereira Pessôa, M. V. (2020). “A roadmap for a leanness company to emerge as a true lean organization”, *Concurrent Engineering Research and Applications*, 28(1), 3-19. doi:10.1177/1063293X19888259

Sobek, D.K., Ward, A.C. and Liker, J.K. (1999) “Toyota’s principles of set-based concurrent engineering,” *Sloan management review*, 40(2), pp. 67–84.

Suwanda, S., Al-Ashaab, A. and Beg, N. (2020) ‘The development of knowledge-shelf to enable an effective set-based concurrent engineering application’, Int. J. Internet Manufacturing and Services, Vol. 7, No. 4, pp.407–427

Suwanruji, P. and Enns, S.T. (2007) “Comparison of supply chain replenishment strategies in a non-capacitated distribution system,” *International Journal of Risk Assessment and Management*, 7(1), pp. 59.

Wang, J. and Terpenny, J.P. (2003) “Learning and Adapting Fuzzy Set-Based Trade-off Strategy in Engineering Design Synthesis,” *International Journal of Smart Engineering System Design*, 5(3), pp. 177–186.

Ward, A.C. and Sobek II, D.K. (2014) *Lean product and process development*. Lean Enterprise Institute. ISBN 978-1-934109-43-4.

Ward, A.C., Liker, J. K., Cristiano, J.J., and Sobek II, D. K., A. (1995) “The second Toyota paradox: How delaying decisions can make better cars faster,” *Sloan Management Review*, 36(3), pp. 43–61.

Womack, J. (2006) “A lesson to be learned,” *Manufacturing Engineer*, 85(2), pp. 4–5.

Yannou, B., Yvars, P.-A., Hoyle, C. and Chen, W. (2013) “Set-based design by simulation of usage scenario coverage,” *Journal of Engineering Design*, 24(8), pp. 575–603.

Zadeh, L.A. (1965) “Fuzzy sets,” *Information and Control*, 8(3), pp. 338–353.

Zhao, X., Minz, J. and Lim, S.K. (2011) “Low-Power and Reliable Clock Network Design for Through-Silicon Via (TSV) Based 3D ICs,” *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 1(2), pp. 247–259.



https://dspace.org/

Physics-based trade-off curves to develop a control access product in set-based concurrent engineering environment

Canan Araci, Zehra; Al-Ashaab, Ahmed; Garcia Almeida, Cesar

2021-08-24
Emerald
https://doi.org/10.1108/IJLSS-10-2016-0061
Canan Araci Z, Al-Ashaab A, Garcia Almeida C. (2022) Physics-based trade-off curves to develop a control access product in set-based concurrent engineering environment. International Journal of Lean Six Sigma, Volume 13, Number 4, 28 July 2022, pp. 824-846

Downloaded from a DSpace repository. https://dspace.org/