Enabling Set-based Concurrent Engineering via Physics-based Trade-off Curves

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Abstract: - There is a huge demand on innovative products which forces companies to develop new products. Lean product development is an approach to support new product development. Set-based concurrent engineering (SBCE) is a process of developing a product in a lean environment. SBCE requires a right knowledge environment which represents the physical characteristics and the performance of the product; hence the design team could achieve a robust design and shorten their time-to-market. Trade-off curves are effective tools to provide and visualise this knowledge environment. This paper presents a process of generating trade-off curves based on understanding the physics of the product. The generated physics-based ToCs are used in a research-based industrial case study to enable two key SBCE activities: (1) comparing alternative design solutions and (2) narrowing down the set of design solutions as well as supporting the design team for decision-making and communication between the departments. It is found that ToCs is a useful tool to visualise the physics knowledge of the product and to communicate this knowledge between stakeholders without a need for an extensive engineering background.

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

1 Introduction

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 [1]–[4]. As a lean product development enabler, SBCE is a knowledge intensive process considering a set of designs concurrently and then gradually narrowing the set, helping to ensure that designs are compatible with their environment and feasible [4]. SBCE dramatically reduces the need for engineering changes [2]. This set-based philosophy also helps to identify and resolve problems as early as possible and ensures that product attributes, including crucial trade-offs, are clearly understood [5]–[7].

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 [8]–[10]. 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 [11], [12]. The most relevant definition to this paper’s context has been made by [4]: 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 [9], [13], [14]. 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 [4], [13]. 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: customer requirements, decision criteria, design parameters, data of the design parameters, and feasible design area [13]–[20].

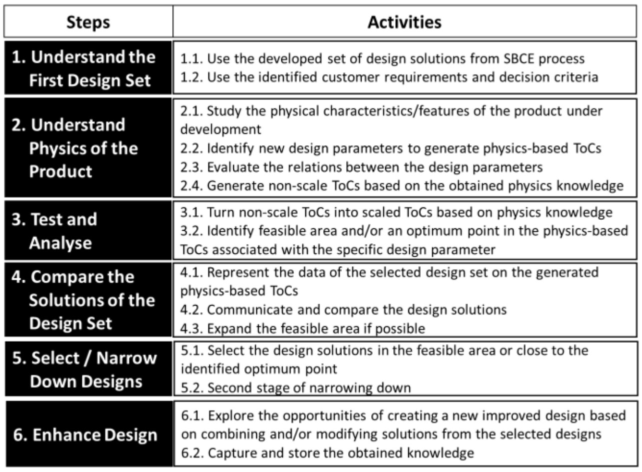
An extensive literature review and industrial field study by [8] show the importance of generating and using trade-off curves to support different activities of product development and, in particular, set-based concurrent engineering (SBCE) approach. According to above mentioned research, it has been found that trade-off curves could enable the following key SBCE activities: (a) Identifying the feasible area, (b) Generating a set of designs, (c) Comparing the alternative design solutions, (d) Narrowing down the set, and (e) Supporting the achievement of a final optimum design solution. Up-to-date the progress of the research developed a process to generate knowledge-based ToCs to enable the first two SBCE activities; identifying the feasible area and generating a set of designs. This process was implemented in the new product development of a card reader of an electronic access control system for an industrial case study validation [8].

Worth to mention that there are three types of ToCs: 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 [21]–[25]. 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 relationships between different variables and make their decision on the optimum design which shows a better performance under certain circumstances.

This paper focuses on presenting a new process of generating ToCs based on the physics knowledge and physical attributes of the product to enable comparing and narrowing down the design set throughout the SBCE. The following section presents this process and demonstrates how to use the generated physics-based ToCs in an industrial case study of developing a new vandalism resistant electronic card-reader of an access control system.

2 The Process of Generating Physics-based Trade-off Curves for a "VR-Card Reader"

This section presents a process of generating trade-off curves based on understanding the physics of the product. Fig. 1 illustrates a diagram of this process. Each step of the process of using ToCs in enabling SBCE has been explained in detail in this section and case study has been presented by following each step.

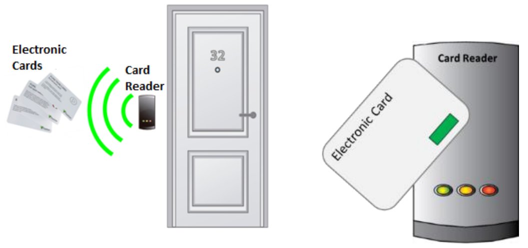


Steps	Activities
1. Understand the First Design Set	1.1. Use the developed set of design solutions from SBCE process 1.2. Use the identified customer requirements and decision criteria
2. Understand Physics of the Product	2.1. Study the physical characteristics/features of the product under development 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

Fig. 1: The process of using ToCs based on the understanding of physics to compare and narrow down the design set throughout the SBCE process

This is a research-based case study using realistic data. The case scenario is to develop a new card reader as illustrated in Fig. 2 that is resistant to vandalism as well as reliable and cost effective. Vandalism could be defined as deliberately damaging the product by, for example, hitting, burning, and pouring liquids. A "card reader" is an important part of an electronic access control system which identifies different users trying to access the system and sends this information to another device that 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). This case study aims to present how to use physics-based ToCs within the following activities:

1. To support designers' decision-making throughout the SBCE process.
2. To enable SBCE process model key activities: Compare design solutions and Narrow down the design sets.



(a) Electronic access control system diagram
(b) The card reader (the product under development)

Fig. 2: The card reader within electronic access control system

2.1 Step 1: Understand the First Design Set

The design 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. Fig. 3 illustrates the design set to be presented in this case study that was produced by the participation of the authors throughout a research-project in 2014. The set consists of 10 front cover as the vandalism actions have direct effect on this component.

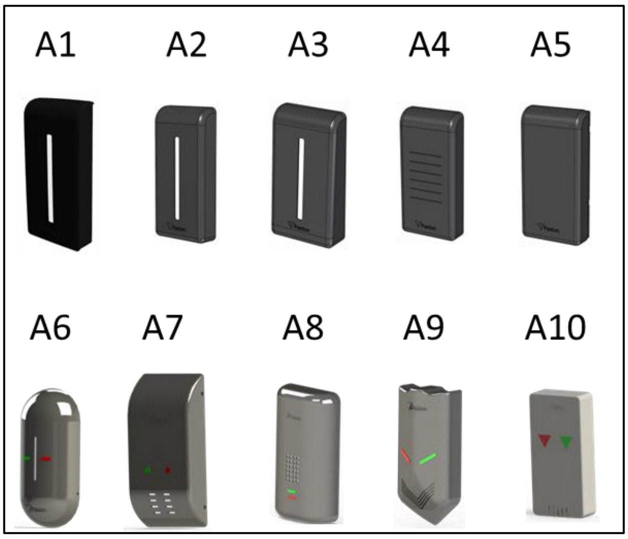


Fig. 3 The set of alternative design solutions of the front cover component of the access control system.

In order to achieve an optimum design solution that addresses the needs of the customer, the PD team should refer to the customer requirements and decision criteria. The design team has used the identified "key value attributes (KVA)" in [4] as a representation of the customer requirements and decision criteria. For further presentation of the case study, the term of "key value attributes (KVA)" will be used. These KVAs are (1) Durability, (2) Reliability, and (3) Cost effectiveness.

2.2 Step 2: Understand Physics of the Product

Activities of this step have been combined and have been presented in non-scale physics-based ToCs. 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.

In the light of the KVAs, results of studying the physics showed that the following design parameters play an important role in the development of a vandalism resistant card reader. Fig. 4 illustrates a diagram of the product.

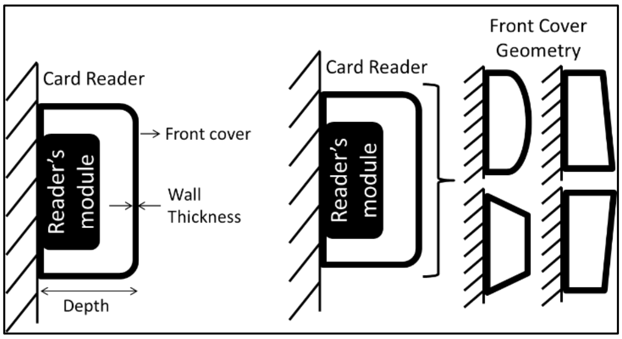


Fig. 4 Illustration of the identified new design parameters (wall thickness, depth, front cover geometry) using the physics-knowledge of the product

The following list presents the identified design parameters reflecting the physics-functions of the VR-card reader and the evaluation of the relationships of these design parameters. Relationships have been illustrated in the non-scale physics-based ToCs. Fig. 5 shows an example of how to illustrate the physics-knowledge of a product in a single diagram for an easy communication between departments and stakeholders.

1. 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. 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 Fig. 4). In addition, the geometry of the front cover could protect the product by reflecting the UV lights.
2. Fire resistance: Product might be damaged when it is exposed to fire. The concept of the fire in this case is trying to burn the product by using a lighter. 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 inner components which will be a positive affect regarding the durability and reliability of the product.

3. Impact resistance: Product might be cracked or damaged by hitting, punching or kicking. Increasing wall thickness and depth will increase the impact resistance. Because the thicker and wider front cover protects the product from being damaged easily. Moreover, different angles of the front cover geometry will protect the product against the vandalism actions better than a flat geometry.
4. Read range: Read range is measured as the distance of the magnetic area created by the reader's module. Thus, once the electronic card reaches this read range, the electronic access system is activated by receiving the radio signals. Increasing wall thickness and depth will affect the read range in a negative way. 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.
5. Cost: Product cost is affected depending on the amount of the material used. A design solution with thicker and wider front cover will require more material which leads to cost increase.

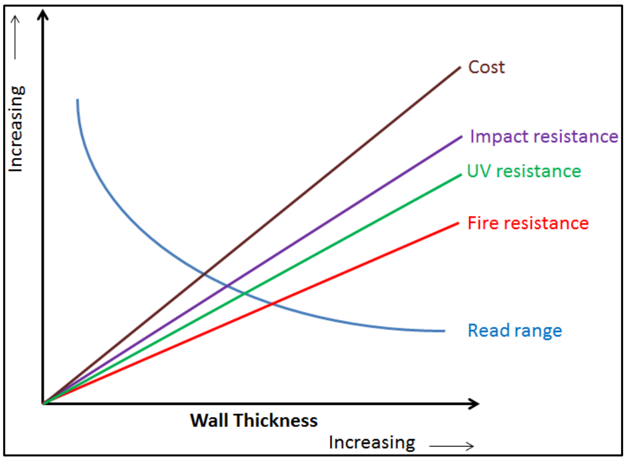


Fig. 5: The non-scale ToC illustrating the relationships between wall thickness and the design parameters: UV resistance, fire resistance, impact, resistance, read range, and cost

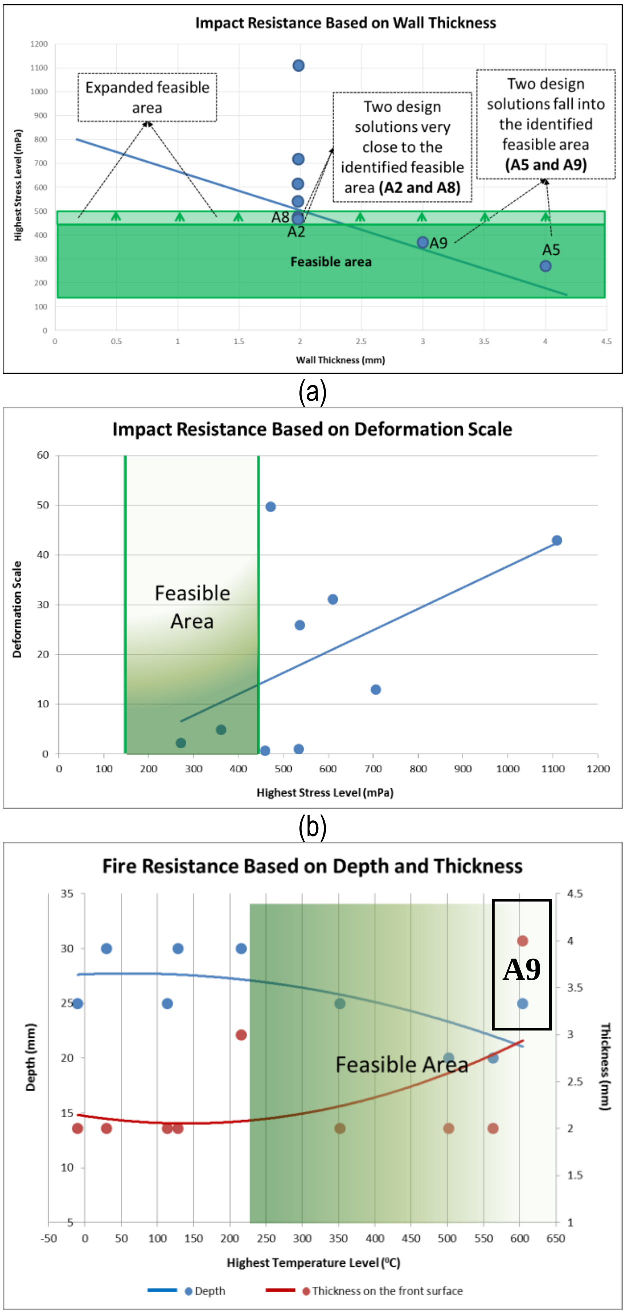
As depicted in Fig. 5, increasing the wall thickness of the front cover will improve the resistance to impact and fire. However, these enhancements come at the expense of rising device-cost due to increased material requirements. Furthermore, the read range of the device will decrease as a thicker wall will weaken radio signals passing through the product.

2.3 Step 3: Test and Analyse

In order to start generating ToCs related to understanding the physics of the product, 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. As it could be understood from the step 2, wall thickness and depth have significant effects on the identified design parameters. In this paper, only impact and fire resistance of the designs will be analysed via structural and thermal simulations in order to illustrate the process in Fig. 1.

Structural analyses were focused on simulating the impact of a hammer, while thermal analyses were focused on simulating the action of a lighter flame. Indicators were used to turn non-scale ToCs into scale physics-based ToCs as result of the structural and thermal analyses; Indicators for structural analysis: (1) Highest stress level (mPa) (related to the impact resistance), (2) Deformation scale (related to the impact resistance); Indicators for thermal analysis: (3) Highest temperature level (°C) (related to the fire resistance). Fig. 6 illustrates the physics-based ToCs that were generated according to the knowledge from the non-scale ToCs identified in Step 2 and data obtained from the structural and thermal analysis.

Optimum point for thermal analysis was considered as a melting point of 230°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°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°C and highest stress level ≤ 450mPa) and illustrated in Fig. 6.



(a)

(b)

(c)

Fig. 6 Physics-based ToCs obtained from non-scale ToCs related to the impact and fire resistance performance of components shown in Figure 3.

2.4 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. The design team will be able to see the differences and similarities between generated design solutions by using generated physics-based ToCs in Step 3. It was found that there are two design solutions fall into the feasible area in Fig. 6(a) and Fig. 6(b) while there are four design solutions in the feasible area of Fig. 6(c). Due to having a good understanding at this stage will help to expand the feasible area. 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. According to Fig. 6(a) and Fig. 6(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.

2.5 Step 5: Select and Narrow Down Designs

During the SBCE process, the design team intends to trade-off and narrow down the set of design solutions. ToCs provide an objective manner to accomplish this task. 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 KVAs and show satisfying performance should also be selected. Therefore, the following solutions are selected from each ToC in Fig. 6;

A2, A5, A8, A9 → Impact resistance based on thickness (Fig. 6(a))

A2, A5, A8, A9 → Impact resistance based on deformation scale (Fig. 6(b))

A2, A3, A4, A5 → Fire resistance based on depth and wall thickness (Fig. 6(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. This is to evaluate design solutions and compare them to each other in order to obtain more optimised values of the design parameters identified in Step 2. Selected design solutions were evaluated and the results have been presented below:

1. A2 and A5 are selected because they meet requirements for both the impact and fire resistance.
2. 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.
3. 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°C.
4. A9 is selected because the values of the design parameters show a promising performance to be considered for design enhancement in the following Step 6.

As result, there are 3 design solutions selected (A2, A5, and A9) for further development of the final optimum design solution.

2.6 Step 6: Enhance Design

This step is 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. Due to the time constraints, this step will be considered as a future work. However, it could be suggested that A9 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.

3 Conclusions

Set-based concurrent engineering (SBCE) is a useful approach to develop a new product. It is essential to provide 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. 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.

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