Knowledge Creation and Visualisation by Using Trade-off Curves to Enable Set-based Concurrent Engineering

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Abstract: The increased international competition forces companies to sustain and improve market share through the production of a high quality product in a cost effective manner and in a shorter time. Set-based concurrent engineering (SBCE), which is a core element of lean product development approach, has got the potential to decrease time-to-market as well as enhance product innovation to be produced in good quality and cost effective manner. A knowledge-based environment is one of the important requirements for a successful SBCE implementation. One way to provide this environment is the use of trade-off curves (ToC). ToC is a tool to create and visualise knowledge in the way to understand the relationships between various conflicting design parameters to each other. This paper presents an overview of different types of ToCs and the role of knowledge-based ToCs in SBCE by employing an extensive literature review and industrial field study. It then proposes a process of generating and using knowledge-based ToCs in order to create and visualise knowledge to enable the following key SBCE activities: (1) Identify the feasible design space, (2) Generate set of conceptual design solutions, (3) Compare design solutions, (4) Narrow down the design sets, (5) Achieve final optimal design solution. Finally a hypothetical example of a car seat structure is presented in order to provide a better understanding of using ToCs. This example shows that ToCs are effective tools to be used as a knowledge source at the early stages of product development process.

Keywords: set based concurrent engineering, trade-off curves, knowledge creation, knowledge visualisation, knowledge reuse, new product development, innovation

1. Introduction

Companies are struggling with introducing good quality and innovative products into the market on time. One reason is that they are facing several challenges during their product development (PD) processes: rework, late design changes, lack of knowledge, and communication problems between departments (Khan et al, 2011). Academics and scholars have focused on defining principles and practices in order to eliminate these challenges and increase PD effectiveness and efficiency (Al-Ashaab et al, 2013; Khan et al, 2011; Sobek and Liker, 1998). Set-based concurrent engineering (SBCE) process model is an effective approach to support PD to address the current challenges.

SBCE explores a set of design solutions in a knowledge-based environment, trade-offs and narrows down these solutions while proceeding in PD until an optimal solution is achieved (Ward and Sobek II, 2014). Knowledge creation has been recognised as one of the most important possessions of a company (Nonaka et al., 2014). In order to survive and sustain successfully in the competitive market, it is inevitable to create a knowledge environment in SBCE to enhance the quality of decision-making throughout the product development process as well as to reuse and share the knowledge. This is done by the provision of a knowledge-based environment and knowledge visualisation using trade-off curves (ToCs).

ToC is a tool to create and visualise knowledge in a simple way to understand the relationships between various design parameters to each other. This paper is presenting a systematic approach to generate ToCs in order to provide with a set of design solutions in the early stages of PD by using SBCE process model in order to provide right knowledge-based environment.

The research approach in this paper consists of four phases: (1) reviewing the related literature, (2) understanding the industrial perspectives of ToC, (3) developing a process to generate and use ToCs and (4) case study validation. In the first phase, the practices of knowledge creation and visualisation using ToCs in different research areas were analysed by an extensive literature review and industrial applications. The review of the related literature is performed to have sound understanding of the meaning of ToC and capturing the good practices as well as to obtain scholars' opinions about the role of ToCs in SBCE. In the second phase, industrial perspectives have been acquired by two major research activities: developing a questionnaire and performing face-to-face interviews in a range of companies. In the third phase, a process of generating and using ToCs was developed based on the information gained from the literature

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review and industrial field study. Finally, the process was validated by using realistic data in a hypothetical example of a new car seat structure development.

This paper is structured in the following manner: next section presents the related literature review by giving an overall definition of ToC and highlighting the differences between knowledge-based and math-based ToCs. After that, the role of knowledge-based ToCs within SBCE is identified. Section three illustrates the results and analysis of performed industrial field study. And then, the process of generating knowledge-based ToCs to enable SBCE application is presented in section 4. Finally, a hypothetical example is demonstrated to have a better understanding of this process.

2. Review of the related key literature

2.1 An overview of trade-off curves

In the literature, researchers have defined trade-off curves in several ways which are similar to each other at some point. For instance, Sobek, Ward and Liker (1999) describe a trade-off curve as that it establishes a relationship between two or more parameters which is more useful than trade-off data. According to Kennedy, Harmon and Minnock (2008), a trade-off curve is a relationship between two or more design decisions and it is the subsystem knowledge from which design alternatives are evaluated and narrowed until the optimal design is chosen and therefore, provides reusable knowledge for future product designs.

At Toyota, “jidoka” refers to visual management, a technique adapted from lean manufacturing to PD in order to simplify complex knowledge using visual tools (Morgan and Liker, 2006), such as trade-off curves, visual project board (Mascitelli, 2006) and health charts (Liker and Morgan, 2011). Trade-off curves are used to evaluate one design attribute against another (Oosterwal, 2010). They visually display subsystem knowledge in a graph from which engineers explore design space (Ward and Sobek II, 2014) and evaluate design alternatives (Kennedy, Harmon and Minnock, 2008). Moreover, trade-off curves avoid the reinvention of previously considered design solutions during prototyping (Womack, 2006).

To conclude, during the conceptual design stage, there are several conflicting parameters that have a major impact on design decision-making. Thus, it is important to identify these conflicting parameters and understand the relationship between them in a visual manner. This is very important in the application of SBCE in order to produce a set of design solutions; hence there are more design parameters to be considered simultaneously. Therefore, ToC is a useful tool to be used in this context.

3. Math-based vs knowledge-based trade-off curves

It is worth to note that ToCs are used in different areas especially to support decision-making. This paper classifies ToCs in two categories based on the way of providing data to generate these ToCs: math-based and knowledge-based. Math-based ToCs are generated by using the data output from simulating engineering applications by mathematical modelling. Knowledge-based ToCs are generated by using facts and knowledge obtained from material providers, previous projects (including failed or incomplete projects), R&D, and prototyping and testing. Therefore, knowledge-based ToCs usually display the knowledge the companies already have or real experiences from engineering activities.

ToCs should have some essential characteristics to be able to enable SBCE process. Therefore, as result of interactions with companies and literature review, authors identified a number of criteria to compare math-based and knowledge-based ToCs: decision support, visualisation, communication, source of data, data reliability, and amount of solutions. Table 1 summarises this comparison according to the identified criteria. Math-based ToCs in these studies are usually used to visualise and compare conflicting objectives subject to constraints and also to support the decision making in multi-objective/criteria optimization. However, these studies show that ToCs data is generated in a mathematical manner depending on assumptions rather than facts and knowledge. Hence, assumptions might be overestimated or underestimated which may lead designers to give a wrong decision.

Additionally, it can be concluded from the literature review that 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. Furthermore, they are able to generate hundreds and thousands of solutions, however, this might cause confusion for designers, also it takes time to compare and evaluate these solutions. It is found that all these ToCs are based on simulations, algorithms, and mathematical programming which include assumptions and uncertainty (Bitran and Morabito, 1999), thus, risk as well as estimation errors (Roemer and Ahmedi, 2004).

Table 1 Comparison between math-based and knowledge-based ToCs

	References	Decision support in product development	Visualisation	Communication	Source of data		Data Reliability		Amount of solutions	
					Algorithms, formulas, etc.	Facts and knowledge	Assumptions and conditions	Real data and experience	Too many	Sufficient
Math-based ToCs	Berkelaar, Buurman and Jess, 1996				*				*	
	Bitran and Morabito, 1999	*	*		*		*	*		*
	Browning and Eppinger, 2002				*		*		*	
	Fine, Golany and Naseraldin , 2005		*		*		*			*
	Panduro et al, 2006	*	*		*				*	
	Richards and Valavanis, 2010		*		*		*		*	
	Roemer and Ahmadi, 2004	*			*		*			
	Vassilvitski and Yannakakis, 2005		*		*		*			*
Knowledge-based ToCs	Correia, Stokic and Faltus, 2014	*	*			*		*		*
	Haselbach and Parker, 2012	*	*	*		*		*		*
	Kennedy, Sobek II and Kennedy, 2014		*			*		*		*
	Levandowski, Forslund and Johannesson, 2013		*	*		*		*		*
	Maksimovic et al, 2012		*			*		*		*
	Michaelis, Levandowski and Johannesson,2013	*	*	*		*		*		*
	Ward and Sobek II, 2014		*	*		*		*		*

On the other hand, knowledge-based ToCs can represent the design limit by separating the feasible design area from the infeasible design area. Therefore, 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, Michaelis and Johannesson, 2014). However, they should be updated carefully to include new technologies; hence innovation can be achieved in new projects.

4. Trade-off curves within set-based concurrent engineering context

Set-based concurrent engineering is a process that 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 communication with other participants until the final solution is obtained (Ward et al, 1995; Sobek, Ward and Liker, 1999). This makes sure that enough knowledge is created to support the decisions and the selections are not rushed (Al-Ashaab et al, 2013; Sobek and Liker, 1998).

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). The main outcomes of these phases are outlined as following:

- Value research. Customer value and innovation level of the product are identified and the project is aligned with the company strategy.
- Map design space. Design team identifies the scope of the design work as well as the feasible design area.
- Concept set development. A set of possible conceptual design solutions is developed and tested at subsystem level. By the meantime, design team captures the created knowledge and utilises this knowledge for evaluation of different sets of design solutions. These solutions are communicated within teams to receive feedback and understand constraints.
- Concept convergence. Intersections of the sub-systems are explored, and integrated systems are tested. The weak solutions are eliminated allowing the optimal design solution to reach the final phase.
- Detailed design. The final set is concluded and final detailed specifications are released.

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:

- Identifying the feasible design solutions area (Khan et al, 2013; Maksimovic et al, 2012; Kennedy, Sobek II and Kennedy, 2014; Morgan and Liker, 2006; Ward and Sobek II, 2014)
- Generating a set of designs (Oosterwal, 2010; Ward and Sobek II, 2014)
- Communicating sets to others (Correia, Stokic and Faltus, 2014; Kennedy, Sobek II and Kennedy, 2014; Khan et al, 2013; Sobek, Ward and Liker, 1999)
- Comparing alternative design solutions (Sobek, Ward and Liker, 1999; Ward and Sobek II, 2014)
- Trade-off and narrow down the set of design solutions (Khan et al, 2013; Sobek, Ward and Liker, 1999)

During 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). Therefore, trade-off curve is a powerful tool to eliminate these challenges.

Although ToC is an important tool as understood from the literature review, there is no systematic approach to generate and use them to enable SBCE applications in PD processes. However, scholars find the following key issues need to be considered in ToCs generation to support decision-making in the PD processes:

- Identifying decision criteria (Levandowski, Michaelis and Johannesson, 2014; Maksimovic et al, 2012). These are related to customer requirements that drive the key design decisions. For example; cost and number of production; emission and fuel consumption.
- Identifying design parameters (Kennedy, Sobek II and Kennedy, 2014; Kerga et al, 2014; Maksimovic et al, 2012). 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 conflictions and the reason behind that. For example material cost against number of production, noise level against product overall size and fuel consumption against pollution.
- Collecting design parameters data (Kennedy, Sobek II and Kennedy, 2014; Levandowski, Michaelis and Johannesson, 2014; Maksimovic et al, 2012). Ranges of data of the identified parameters need to be captured from, for example, previous projects, testing and simulation.

The industrial perspective of this research has been demonstrated in the next section, also supports academic studies on using ToCs to enable SBCE.

5. Industrial perspective of trade-off curves

The industrial perspective of using ToCs has been captured by performing face-to-face interviews or WebEx using a semi-structured questionnaire in a range of companies from the automotive, aerospace and engineering sectors. These companies either have initiatives to apply SBCE or are interested in using SBCE to support their product development processes. The following are the results of the key activities that would be supported by ToCs and key activities to generate ToCs.

Participants were asked to rank the importance and efficiency of using ToCs in the key activities of their current product development processes – which are listed below;

- To identify the feasible area
- To generate a set of conceptual designs
- To compare possible conceptual designs
- To narrow the set of conceptual designs
- To enable key decision-making

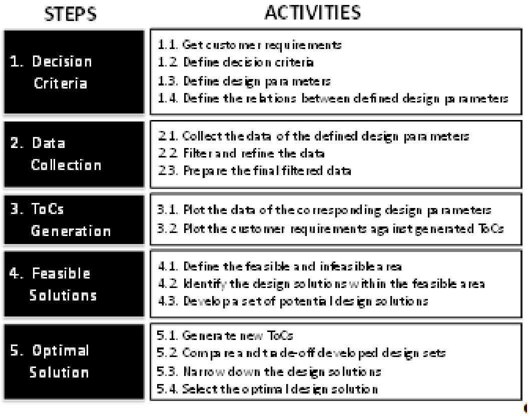
Responses from the participants showed that all these listed PD activities are important; however, the current industrial practices are not efficient. For example, using ToCs to generate a set of conceptual designs is very important to most of the participants (above the average with an importance rank of 85%) whereas they indicate that their current practices are not very efficient (below the average with an efficiency rank of 45%). This might be because of the lack of understanding how and where to use ToCs in PD processes effectively. It is found that using ToCs in PD activities is significantly important from industrial point of view. This finding leads to another question of how to generate ToCs. As mentioned in the related literature review in Section 2.3, scholars recommended some activities to generate ToCs, although a systematic approach couldn't be found. In order to understand the industrial perspective of how to generate ToCs, a list of activities were suggested below to the participants to rank according to the importance and efficiency of using these activities in generation of ToCs;

- Defining decision criteria
- Defining parameters
- ToC data collection
- Plotting customer requirements
- Defining feasible/infeasible area

The results showed that although all the listed activities are important to generate ToCs, efficiency of their current industrial practices is not good enough. This could be due to the fact that there is no systematic approach of generating ToCs in PD processes which clearly explains how to implement these activities and use the generated trade-off curves effectively to support the listed activities above. Literature review and industrial field study show that there is no clear framework and sequence of stages that will assist the knowledge provision to enable SBCE applications. Additionally, the role of ToCs within SBCE process model is not defined clearly. Therefore, this paper proposes a systematic process to generate knowledge-based ToCs to enable effective SBCE which is presented in the following section.

6. The process of generating trade-off curves to enable set-based concurrent engineering

This paper presents a systematic process which capable of generating knowledge-based ToCs and using these ToCs in the generation of design solution sets which is an SBCE key activity. As illustrated in Figure 1, this process consists of five main steps which are broken down further into different activities. Although a sequential approach has been communicated, the chronological position of some activities within the process may be interchangeable.



STEPS	ACTIVITIES
1. Decision Criteria	1.1. Get customer requirements 1.2 Define decision criteria 1.3. Define design parameters 1.4. Define the relations between defined design parameters
2. Data Collection	2.1. Collect the data of the defined design parameters 2.2 Filter and refine the data 2.3. Prepare the final filtered data
3. ToCs Generation	3.1. Plot the data of the corresponding design parameters 3.2 Plot the customer requirements against generated ToCs
4. Feasible Solutions	4.1. Define the feasible and infeasible area 4.2 Identify the design solutions within the feasible area 4.3. Develop a set of potential design solutions
5. Optimal Solution	5.1. Generate new ToCs 5.2 Compare and trade-off developed design sets 5.3. Narrow down the design solutions 5.4. Select the optimal design solution

Figure 1 The process of generating ToCs to enable SBCE

Step 1. Decision Criteria

- Get customer requirements: Customer requirements are the minimum requirements to satisfy stakeholders' needs. Therefore, customer requirements should be understood clearly to identify the decision criteria and the key design parameters in order to generate appropriate ToCs.
- Define decision criteria: Key design decisions are driven by the decision criteria that are identified related to the customer requirements.
- Define design parameters: These parameters give the special characteristics of the product under development. The different design parameters might be conflicting with each other. Visualisation of this confliction by using ToCs supports decision making of PD team. 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. PD team could identify the design parameters by brainstorming.
- Define the relations between defined parameters: The PD team should identify the plausible relations between at least two identified design parameters in order to project on the axis of ToCs. PD team could define as many ToCs as needed until they achieve the confidence of accurate decision-making.

Step 2. Data Collection

- Collect the data of the defined parameters: Data to be plotted on the ToCs could be collected from, for example, previous projects, testing and prototyping, material providers, suppliers, R&D projects, etc.
- Filter and refine the data: After data collection, it might occur that there are unavailable data which are not recorded previously, do not exist in the data source, or cannot be generated at the time being. Thus, parameters which do not have data should be removed from the parameters list in order to prevent confusions and mistakes while generating ToCs.
- Prepare the final filtered data: The data spreadsheet should be organised in order to easily select and use the data to generate ToCs.

Step 3. ToCs Generation

- Plot the data of the corresponding parameters: After data collection, this design parameters data should be plotted on the related axis according to the defined relationships in Step 1.4.
- Plot the customer requirements against generated ToCs: Customer requirements are the determinant values of the design boundaries that the PD team could generate new designs which meet the needs for the current project. In order to identify feasible design solutions, customer requirements should be plotted on generated ToCs.

Step 4. Feasible Solutions

- Define the feasible and infeasible area: The feasible area should be highlighted clearly to be able to spot the possible design solutions fall into this area.
- Identify the design solutions within the feasible area: PD team projects the customer requirements against the knowledge-based ToCs in order to identify the feasible design solutions. These solutions could be from either

complete/incomplete previous projects or R&D projects. Information about all these solutions could be obtained from share folder of the previous solutions and company database, for example, PLM or PDM.

- Develop a set of potential design solutions: Activities 4.1 and 4.2 are performed for all generated ToCs. After that, the possible design solutions are collected from each ToC with the information of decision criteria that they are addressing. Hence, these possible design solutions from each ToC will develop a set of potential solutions.

Step 5. Optimal Solution

This step is to convert developed potential design solutions to a final optimal solution using SBCE process model.

- Generate new ToCs: After developing a set of potential design solutions from previous projects, PD team could decide if they need new ToCs to be able to compare the design sets. If needed, the process should be repeated from defining design parameters (step 1.3) to feasible area definition (step 3). New ToCs are generated in the light of previously identified customer requirements and decision criteria. The data for these new ToCs could be obtained from the testing and simulations.
- Compare and trade-off developed design sets: Generated ToCs are studied and analysed by the PD team and communicated with other departments in order to discuss the product lifecycle issues such as detailed design, manufacturability, sales, services, maintenance, and recycling. During discussion session, PD team will have insights from the generated ToCs to compare and trade-off the potential design solutions.
- Narrow down the set of design solutions: After comparing and trading-off the set of designs, the weak solutions should be eliminated from the set. These weak solutions could be the ones that are not compatible with the company benefits or have constraints in any stage of the product lifecycle. For example, a design should be eliminated that is considered as impossible to be manufactured with the available technology of the subject company.
- Select the optimal design solution: The optimal design solution must be the one that meets all the requirements and the criteria identified at the beginning of the project. In order to find out this solution among the narrowed set, PD team may require more knowledge-based ToCs acquired from real data and prototyping. The design solution shows the best results is selected as a final optimal design.

7. Hypothetical example of knowledge-based ToCs to enable SBCE application

This section presents the use of the process shown in Figure 1 to generate several ToCs to enable the application of SBCE in an automotive company that produces car seat structure as illustrated in Figure 2. This is a research-based case study using realistic data. The case scenario is to come up with a new design solution of passenger car seat. This hypothetical example aims to present how to use knowledge-based ToCs within the following activities;

- To support product development team's (PD team) decision-making for an appropriate sheet metal selection,
- To enable SBCE process model key activities: (1) Identify the feasible design space, (2) Generate a set of conceptual design solutions, (3) Compare design solutions, (4) Narrow down the design sets, (5) Achieve final optimal design solution.

The following is presenting a systematic use of the process of generating ToCs. Car seat structure will be named as the "final product" within the presentation of this hypothetical example.

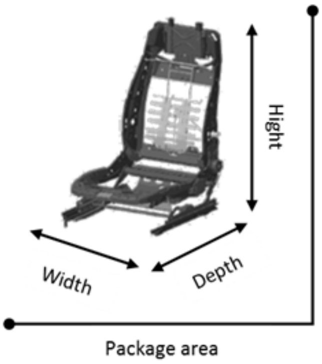


Figure 2 Illustration of a car seat structure (the product under development)

Step 1. Decision Criteria

Get customer requirements: The following are the given customer requirements of the car seat:

- Light and strong metal material
- Durable car seat
- Low cost seat
- The small seat size

Define decision criteria: The analysis of the customer requirements helped PD team to identify the following decision criteria:

- High durability: The final product should be strong enough against the crashes or load,
- Low cost: This is the cost of the final product which includes the material cost and manufacturing cost,
- Low weight: The final product should be light as much as possible by providing the required strength.
- Small package area; Dimensions of the final product should not exceed the determined area within the car.

Define design parameters: PD team identified the design parameters by breaking down the final product into parts: material type, joining process and shape of the product. For example, material type and joining process affect the durability, cost and weight of the product while the shape would have an impact on package size. In this hypothetical example, PD team focused on defining design parameters that are related to the material type and the shape.

- Durability is related to the following parameter;
  - Maximum tensile strength: The higher tensile strength means the stronger material.
- Cost is related to;
  - Material cost: Different characteristics of the material affect the cost according to the elements it include or the production of the material.
- Weight is related to;
  - Density: Density is a determinant parameter of weight.
- Package size is related to;
  - Overall car seat design: The design of the car seat structure should fit into the identified package area.
  - Overall car seat size: The size of the car seat structure should not exceed the identified package area.

Define the relations between defined parameters: In this case the following pairs of the parameters give a meaningful knowledge to the PD team;

- ToC 1 Material cost vs maximum tensile strength: In order to see if the stronger material costs more. The relationship between the material cost and maximum tensile strength will show the conflicts between the durability and cost decision criteria.
- ToC 2 Density vs maximum tensile strength: In order to increase the strength, additional elements might be included within the material. This process increases the weight of the material. This relationship will show how the tensile strength changes with different densities of the materials. Thus, designers will have insights about the confliction between the durability and weight decision criteria.
- ToC 3 Material cost vs Density: In order to see the cost range of materials with different weights. This relationship is to see the conflicts between the cost and weight decision criteria.

Step 2. Data Collection

Collect the data of the defined parameters: Data could be collected from material providers and crash performance tests of previous projects of the collaborating company. Table 2 presents the collected metal data which includes different material types.

- Filter and refine the data: In this case study this step was not required.
- Prepare the final filtered data: In this case study this step was not required.

Table 2 Metal data for car seat structure collected from material providers

	Sheet Metal	Max Tensile Strength (N/mm^2)	Density (Kg/m^3)	Material Cost (£/tonne)
1	Material 1	135	1.74	2,000
2	Material 2	270	2.7	1,500
3	Material 3	380	7	400
4	Material 4	545	7.5	700
5	Material 5	580	7.85	800
6	Material 6	615	8	950

Step 3. ToCs generation

Plot the data of the corresponding parameters: Three trade-off curves were generated according to the defined relationships between the related design parameters (presented in step 1.4) as shown in Figure 3. These ToCs are;

- ToC 1 – Durability and Cost
- ToC 2 – Durability and Weight
- ToC 3 – Weight and Cost

Plot the customer requirements against generated ToCs: Provided customer requirements are plotted against the related ToCs.

Step 4 Feasible solutions

Define the feasible and infeasible area: PD team set achievable realistic system targets based on their domain knowledge to be able to meet customer requirements. These targets are as following:

- Maximum tensile strength should be between 350 and 550 N/mm2,
- Density could be accepted less than 7 kg/m3,
- Material cost should not exceed £1,000 per tonne.

These targets are plotted against the generated ToCs. Feasible areas for each ToCs are illustrated in Figure 3.

Identify the design solutions within the feasible area: After identifying the feasible area for each ToC, PD team was able to locate the feasible solutions. These solutions are presented below:

- From ToC 1: Material 3 (Mild Steel) and Material 4 (High strength steel) meet durability and cost requirements
- From ToC 2: Material 3 meets durability and weight requirements
- From ToC 3: Material 3 meets weight and cost requirements

It is seen that there are two materials extracted from the generated ToCs out of six material types in total. While Material 3 meets all requirements for sheet metal selection; durability, cost, weight, Material 4 meets only durability and cost.

Develop a set of potential design solutions: Two suitable materials (Material 3 – mild steel and Material 4 – high strength steel) are hypothetically selected from each ToC that meet certain decision criteria as aforementioned. After that, PD team generates possible design solutions by using these two materials to be able to see the package size performance of each design. As result, eight design solutions are generated from previous projects.

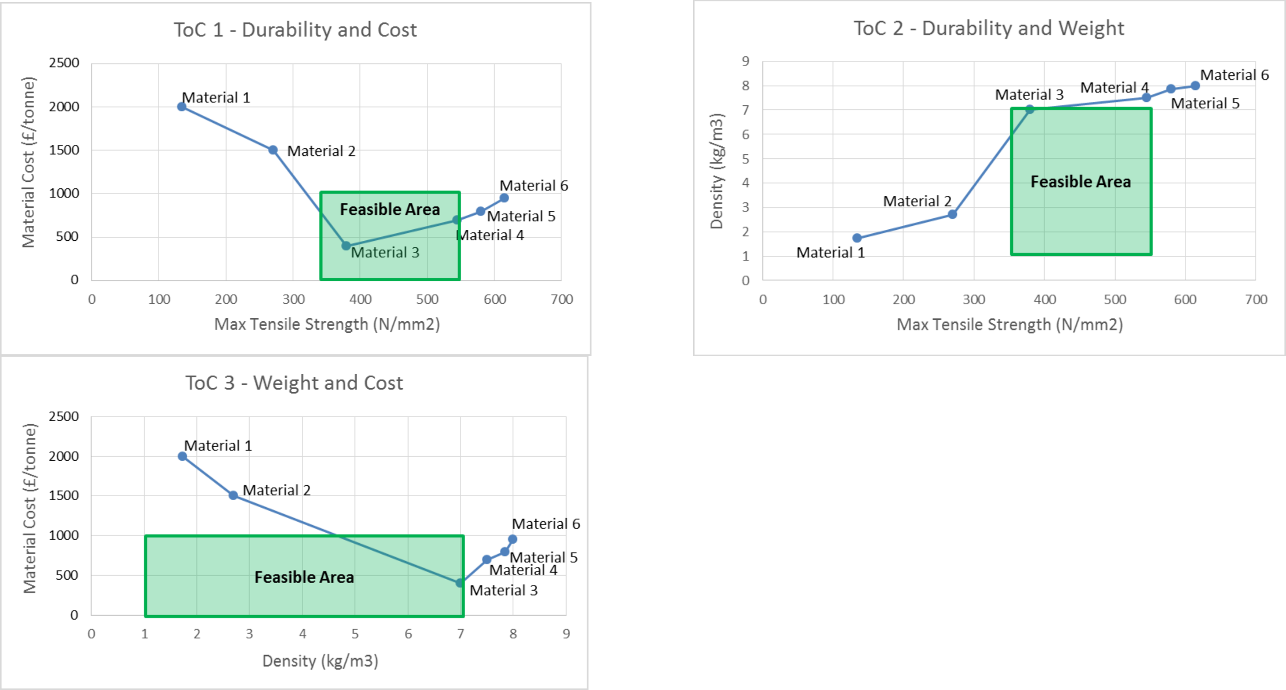


Figure 3: Knowledge-based ToCs to support decision-making on an appropriate material selection for the car seat structure

Step 5. Optimal solution

Generate new ToCs: PD team identified new design parameters related to the project's customer requirements and decision criteria. These design parameters are;

- Sheet metal thickness: Increasing the sheet metal thickness increases the strength of the material, thus the product shows more durable performance. On the other hand, thicker sheet metal causes additional material cost and heavy final product.
- Weight/package area ratio: This is the amount of the sheet metal falls into an identified package area. This ratio is expected to be low due to weight considerations of the final product.
- Crash performance: This parameter is to present the strength of the designs against crashes in order to ensure durability requirement achievement.
- Weight: This parameter is the weight of the final product design to ensure the weight requirement achievement.

After identifying new design parameters, plausible relationships between them were identified as following;

- ToC 4 Sheet metal thickness vs weight/package area ratio: These two design parameters an impact on weight and package size of the car seat structure. PD team expects the lower weight/ package area ratio as the aim is to achieve low weight and small package size while achieving a proper sheet metal thickness. The ToC of this relation was used to compare the possible design solutions for set narrowing.
- ToC 5 Weight vs crash performance: This relation was identified to be able to see the impact of increasing weight on the crash performance of the design solution. The ToC of this relation was used for selection of an optimal design solution after narrowing down the solutions.

PD team hypothetically generated eight design solutions using Material 3 and Material 4. Table 3 presents the realistically generated data of weight/package area ratio with different sheet metal thicknesses. Data in Table 3 is plotted in ToC 4 as shown in Figure 4.

Table 3 Realistic data from hypothetically generated potential design solutions

	Total Design Weight to Package Area Ratio (Kg/m^2)			
Sheet Metal Thickness (mm)	Previous Design Solutions	Results for Material 3	Previous Design Solutions	Results for Material 4
0.5	Design 1	3.81	Design 2	4.51
0.6	Design 3	4.59	Design 4	4.89
0.7	Design 5	5.05	Design 6	5.33
0.8	Design 7	6.21	Design 8	7.34

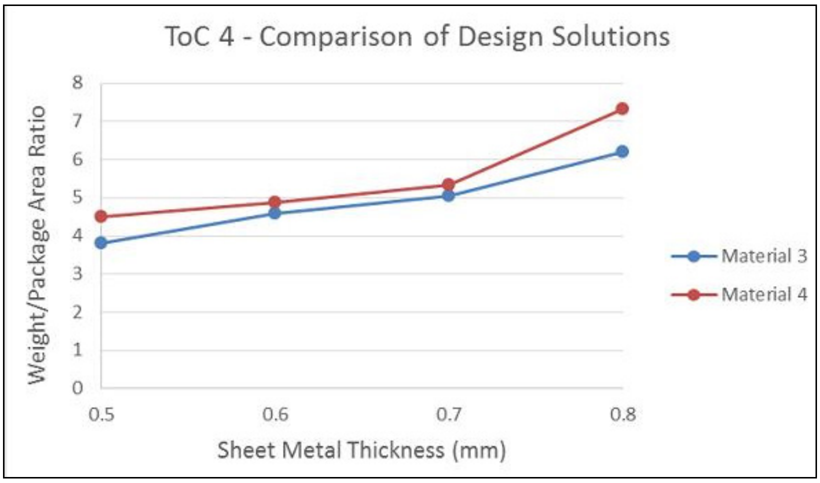


Figure 4 Comparison of eight different design solutions of Material 3 and Material 4.

Compare and trade-off developed design sets: The ToC 4 in Figure 4 is generated to be able to compare the possible design solutions of Material 3 and Material 4. As result of studying and analysing the ToC 4, PD team could see that Material 3 showed better weight/package area ratio than Material 4 with different sheet metal thicknesses. For example, for a 0.5 sheet metal thickness, Material 3 has 3.81 ratios while Material 4 is 4.51.

Narrow down the set of design solutions: As result of compare and trade-off activity, since the aim is to select a light, strong and cost effective material PD team decided to choose Material 3 for further concept development until achieving the optimal design solution. Thus, the set was narrowed down from 8 to 4 design solutions.

Select the optimal design solution: After eliminating the set from unsuitable design solutions, PD team had a better idea about the remaining design solutions to be able to make their decision on the optimal design solution. ToC 5 was generated for further comparison in order to ensure the accuracy of the final design (see Figure 5).

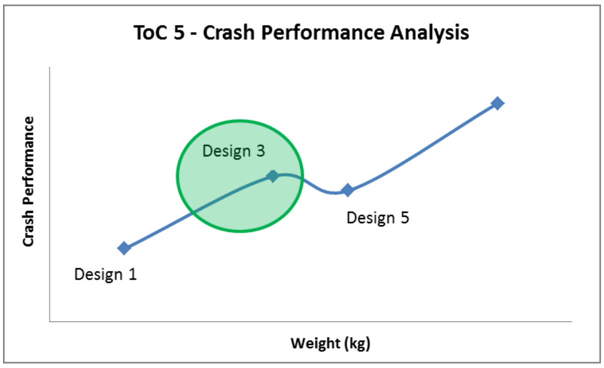


Figure 5 Crash performance analysis for optimal design selection

As it can be seen in Figure 5, four different design solutions with Material 3 show different weight and crash performance results. It can be said that there is a linear relation between weight and crash performance. The heavier product shows better crash performance in three designs out of four as the crash performance of Design 5 is slightly lower than the Design 3. Ideally, PD team intended to select the highest crash performance which is Design 7, however, Design 7 would be too heavy to meet weight decision criteria. On the other hand, Design 1 is the lightest design solution which is required by customer, while its crash performance does not meet the durability decision criteria. Therefore, PD team selected Design 3 since it meets all the identified decision criteria and customer requirements for the current project.

8. Discussion of the results

The hypothetical example of a passenger car seat structure presented that ToCs could be used as a decision support tool while they enable the aforementioned key activities of SBCE process model. Figure 6 illustrates the overall approach step by step that was used in this hypothetical example.

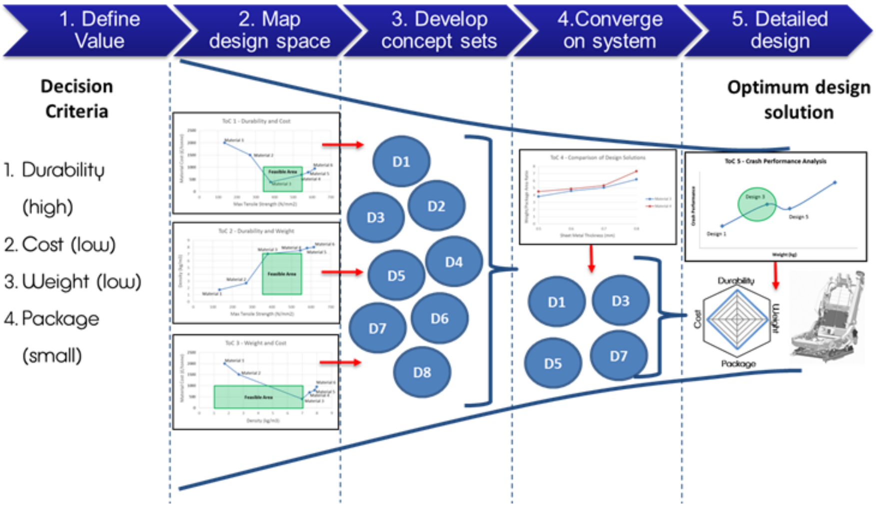


Figure 6 Overall approach to using knowledge-based ToCs within the SBCE process model

First of all three ToCs were generated by using the previous projects' knowledge in order to select an appropriate material that could meet durability, cost and weight requirements. Two materials, Material 3 and Material 4, were selected as suitable solutions from feasible areas of the generated knowledge-based ToCs. Identifying the feasible area is one of the key activities of SBCE. It is seen that ToCs is a successful tool to complete this activity as well as developing a set of design solutions. PD team developed the set including eight designs by using the knowledge from the generated ToCs. These solutions were visually displayed in ToC 4 in order to compare and communicate with other departments in the company. Thus, it is understood that ToCs facilitates communication within the organisation since the knowledge is represented in a visual manner. Additionally, ToCs facilitated the presentation of the relations between essential design parameters, hence the PD team could compare and trade-off the eight design solutions and narrowed down four solutions. These remaining four solutions met identified customer requirements and decision criteria, however, in order to select the best design, PD team generated ToC 5 which represented the knowledge for decision-making based on durability and weight. Finally, Design 3 was selected which satisfies all customer requirements and decision criteria. It can be said that this hypothetical example presented how to generate ToCs as well as how to use generated ToCs to enable SBCE process. Furthermore, the knowledge stored in ToCs could be reused in future projects; hence the discarding knowledge would be prevented.

9. Conclusion

Literature review shows the importance of using ToC to support different activities of PD and in particular SBCE. This research classifies ToCs into two categories: math-based ToCs and knowledge-based ToCs. Math-based ToCs are generated by data which is obtained from mathematical programming, algorithms, and formulas. This will be based on several assumptions as well as the need for generating new data set for the future projects. In addition, these data sets require more substantial engineering efforts to generate the right set of conceptual design solutions. On the contrary, knowledge-based ToCs are based on fact and proven experience of the previous and R&D projects. Hence, they provide appropriate conceptual design solutions.

The evidence from both literature review and industrial field study show the need for a systematic process for generating knowledge-based ToCs to enable SBCE applications. This research found that ToCs could enable SBCE with the following key activities: Generating the set of conceptual design, comparing the design, trade-off between the solutions, narrowing down solutions, and finally supporting the generation of the final optimal design solution. This paper has presented up-to-date research results of a process of generating ToCs which consists of five steps with several tasks within them. A research-based hypothetical example of an automotive car seat has been used to evaluate the effectiveness of the proposed process for generating knowledge-based ToCs from realistic data. The key findings of the case study show that the proposed process provided the required knowledge environment in a visual way by using ToCs. Thus, the PD team could define and trade off the conflicting design parameters of the product under development in an easy and quick manner. Additionally, the generated ToCs helped the PD team to communicate the knowledge with other departments with an easy understanding of the data trends. Finally, these ToCs have been used to generate a hypothetical conceptual set of design solutions for the application of SBCE. Future work is to enhance the process in order to enable all the listed key activities of SBCE with real case studies.

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