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Trade-off Curves Applications to Support Set-based Design of a Surface Jet Pump

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Abstract

Knowledge has become the most important asset of companies, especially in improving their product development processes. The set-based design approach is an efficient way of designing high quality, optimised designs. However, it requires a proven knowledge environment. Trade-off curves (ToCs) have the capability of providing the right knowledge and displaying it in a visual form. Although there are a few applications of ToCs that have recently been published in the literature, none of them demonstrates an integrated implementation of ToCs throughout the SBCE process. This paper presents the integrated use of ToCs, based on both physics-knowledge and proven knowledge, in order to compare and narrow down the design-set and to achieve an optimal design solution. These are key activities of the SBCE process model. Since an accurate, documented and visual knowledge environment is created by the use of ToCs within SBCE, the integrated approach proposed in this paper plays a vital role in eliminating the need for prototyping and testing at the early stages of product development. The integrated approach was implemented in an industrial case study for a surface jet pump. Surface jet pumps are used to increase the production rate of low-pressure oil/gas wells. It has been found that through ToCs, the conflicting relationships between the characteristics of the product can be understood and communicated effectively among the designers. This facilitated the decision-making on an optimal design solution in a remarkably short period of time. Furthermore, the surface jet pump resulting from the case study achieved an increase of the oil/gas production by nearly 60%.

Keywords: lean product development; set-based concurrent engineering; trade-off curves; creating knowledge; visual knowledge; oil and gas production; surface jet pump.

1. Introduction

The current environment on the global market forces companies to develop new products in a cost- and time-efficient manner, in order to be able to address the needs of customers. Set-based design, which is also referred to as set-based concurrent engineering (SBCE), is a core enabler of lean product development. SBCE provides a systematic process model for new product development [1–3]. The main principle of SBCE is to explore a set of design solutions at the front end, and trade-off and aggressively narrow down these solutions while proceeding in product development until an optimal solution is agreed upon [2, 4, 5]. SBCE also addresses several challenges that companies face in the early stages of design. Rework, required due to the lack of knowledge, is one of the main challenges [6]. Additionally, there are often a number of conflicting design parameters, hindering the decision-making during the conceptual stage of the product development process. The appropriate identification, understanding and visualisation of relationships between these parameters is of utmost importance. Therefore, academics recommend the use of trade-off curves as one of the knowledge sources [7, 8].

Trade-off curves are a tool to create and visualise knowledge in a simple way, in order to understand the conflicting interactions of design parameters. The knowledge thus created can be based on the facts, information, and experience from

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previous projects of the company. Moreover, data obtained by understanding the physical characteristics of the product can be turned into physics-knowledge. ToCs, as an effective lean tool, have the capability of generating this knowledge environment [7].

Trade-off curves have been widely used from the 1960s onwards [9], having been applied across a range of disciplines from finance and environmental science to engineering and computer science. Most of the studies in these disciplines have used a type of trade-off curve that is math-based in order to solve multi-objective optimisation problems. Multi-objective (or multi-criteria) optimisation problems are those which have more than one conflicting objective function to be satisfied in order to achieve the optimum solution [10]. However, these trade-off curves are developed by using algorithms and mathematical calculations rather than real data, experience and knowledge. Therefore, math-based ToCs may facilitate the decision-making, but any decision will be dependent on several assumptions and uncertainties inherent in the calculations [7].

On the other hand, there are two types of ToCs that are generated by data from real data sources. One is referred to as knowledge-based ToCs, where the data is collected from material providers, manufacturers, previous projects (including failed, successful, commercial and research based projects), R&D, prototyping and testing. Thus, knowledge-based ToCs are generated by using proven knowledge which represents facts. The second type of ToCs are physics-based ToCs. These ToCs are generated using data obtained from an understanding of the fundamental physical characteristics and mechanisms of the product.

It is also stated in the literature that SBCE requires a proven knowledge environment. The characteristics of this environment have been identified as being visual and easy to communicate, being based on real data/facts with minimum uncertainty, and being reusable. Both knowledge-based and physics-based ToCs address the need of creating such an environment. However, there is no integrated process for the application of these ToCs within the SBCE process. Therefore, this paper aims to present how to support the set-based design of a new product by using knowledge-based and physics-based ToCs, thereby enabling key SBCE activities in an integrated way. These key activities are: 1) Comparing possible design solutions, 2) Narrowing down the design-set, and 3) Identifying the optimal design solution.

An experimental research approach has been followed for this paper. The processes for creating knowledge-based and physics-based ToCs are presented below. Furthermore, the integration of these processes within the SBCE process model is demonstrated in the next section. In section 3, the integrated approach has been implemented in the industrial case study for a surface jet pump, which is used to increase the production rate of low-pressure oil/gas wells. Data for the industrial case study was collected from material suppliers, manufacturers, previous projects, and simulations that are based on an understanding of the physics of the product. Computational fluid dynamics (CFD) analyses were performed for different design solutions in order to evaluate the design performance. "Ansys" software was used for the simulations. Finally, the findings of the industrial case study are discussed and complemented by a conclusion.

2. The integrated use of trade-off curves within SBCE

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 design solution is obtained [3, 9]. 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 [12]. Physics-based and knowledge-based ToCs are used to enable key activities of this model. These key activities are as follows:

1. Identify the feasible design area,
2. Generate a set of design solutions,
3. Compare possible design solutions,
4. Narrow down the design-set,
5. Achieve the optimal design solution.

Fig. 1 shows the integrated use of both knowledge-based and physics-based ToCs within the SBCE process model. This approach may change according to the complexity of the product, the level of innovation, and the needs of the designers. As shown in Fig. 1, the definition of customer value is formalised at the outset, and the physical characteristics of the product are understood during the phase "1. Define Value". According to the obtained information, related ToCs are generated in "2. Map Design Space" in order to identify the feasible design area where the created product designs are considered as feasible for implementation. Fig. 2 demonstrates how to generate knowledge-based ToCs and Fig. 3 illustrates the process for generating physics-based ToCs. These two types of ToCs can be combined into only one trade-off curve, depending on the data available for the product. After generating ToCs, designers are able to identify the feasible solutions. These feasible solutions can be used in different forms in order to develop the design-set. These forms are:

1. Reusing the existing feasible design without making any changes,
2. Minor modifications,
3. Major modifications,
4. Creating a new design solution using inspiration from existing feasible designs.

By consulting the generated ToCs, designers can compare different possible design solutions and select the suitable designs to narrow down the design-set on the component level. In the "4. Converge on System" stage, new ToCs can be generated based on the physics-knowledge of the product. Thus, designers will be able to evaluate different configurations and further narrow down on the system level, until the optimal design is identified.

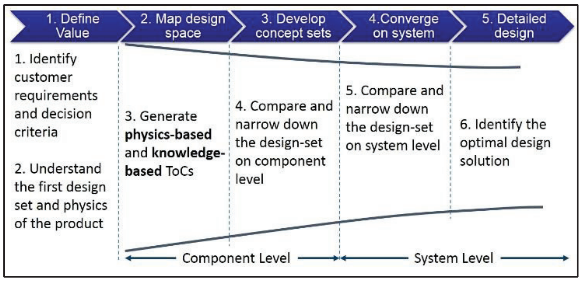
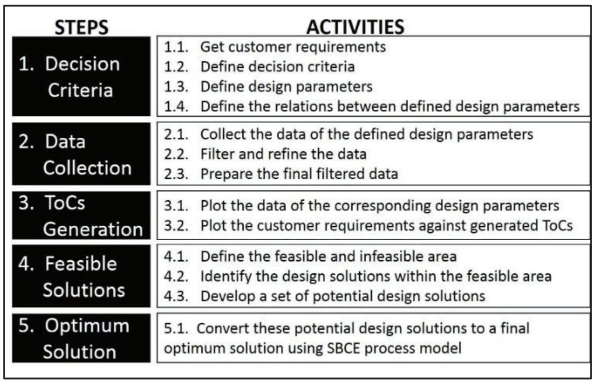
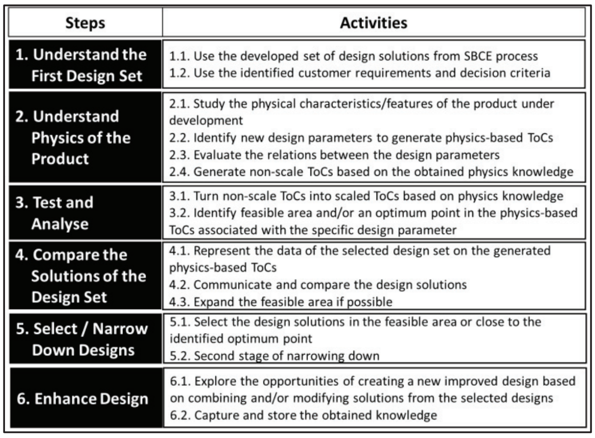


Fig. 1. Integrated overall view of using ToCs within the SBCE process model



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. Optimum Solution	5.1. Convert these potential design solutions to a final optimum solution using SBCE process model

Fig. 2. The process for generating knowledge-based ToCs [7]



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. 3. The process for generating physics-based ToCs

3. Industrial case study for a surface jet pump (SJP)

Surface Jet Pumps are relatively simple devices used to increase the production rate and to revive “dead” wells in the oil and gas industry. The general function of an SJP is to increase the pressure of LP (low-pressure) fluids, an application which is drawn upon at different stages of the production process. Compared to traditional methods of increasing pressure, such as through the use of compressors, SJPs are highly cost-efficient solutions that provide the same performance. SJPs utilise the Venturi effect [13], in which kinetic energy from a high pressure (HP) source is used to increase the pressure of the LP medium [14]. Fig. 4 illustrates the key components of a SJP.

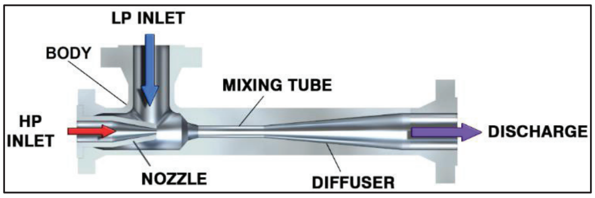


Fig. 4. Key components of a surface jet pump (SJP)

3.1. Identify customer requirements and decision criteria

The following requirements were provided by the customer:

- High mechanical performance,
- Reduced manufacturing cost and time,
- Material: Carbon steel,
- Reduction in weight,
- Maximum allowable pressure is 571 psi,
- Removable nozzle and a fixed mixing tube with a diffuser,
- Meeting oil and gas standard ASME B31.3.

Considering these customer requirements, a group of researchers used the brainstorming methodology and identified the following decision criteria which are related to the customer requirements:

1. Design performance - Determines the production rate of the SJP at constant initial conditions.
2. Manufacturability – Related to the complexity of the design and manufacturing challenges associated with it.
3. Cost– Refers to the manufacturing cost of the product.

The identified customer requirements and decision criteria indicated that the focus should be on the following components: nozzle, mixing tube and body.

3.2. Understand the first design-set and the physics of the product

The identification of the customer requirements and decision criteria creates an understanding of the fundamental features and physical characteristics of the product. Depending on this obtained knowledge, designers develop a design-set for each component under consideration (nozzle, mixing tube and body). The design-set of this case study is shown in Fig. 5. Since an understanding of the physical characteristics of the product is essential, the principle of the SJP, based on the physical mechanisms of the components and the fluid, is described below. When the high-pressure fluid passes through the nozzle, its velocity increases significantly as a result of potential energy (pressure) being converted into kinetic energy (velocity). This reduces the downstream pressure from the nozzle and generates a low-pressure zone which causes the flow of the fluid from the LP well. The HP motive flow carries the LP fluid through the mixing tube, causing a transfer of energy and momentum between both fluid streams. At the outlet of the mixing tube, the mixture is discharged through the diffuser in order to gradually reduce the velocity and recover the pressure [14].

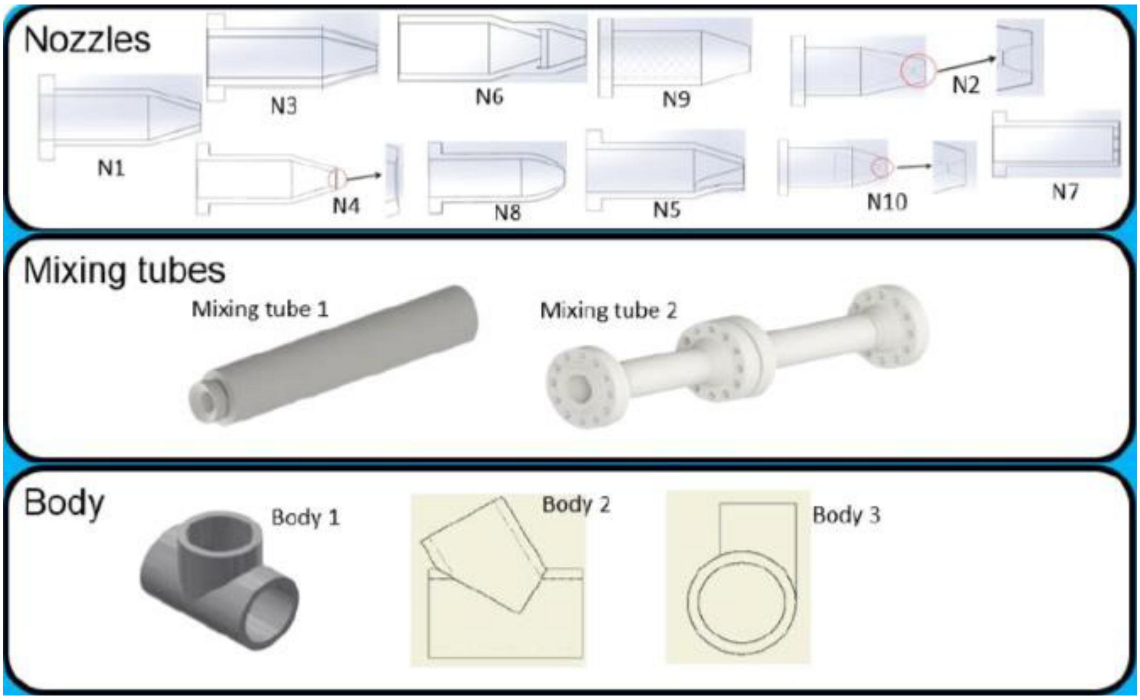


Fig. 5 Developed design-set for each component

3.3. Generate physics-based and knowledge-based ToCs

Using the obtained physics-knowledge, non-scale physics-based ToCs are generated for each component. Fig. 6 visualises that a higher nozzle downstream velocity increases the drop of the pressure and the suction of the entrained LP fluid. Thus, the production rate increases.

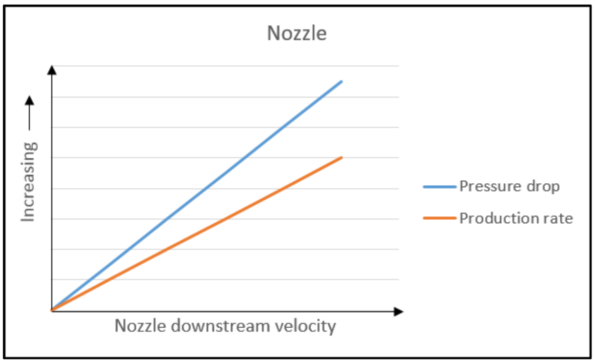


Fig. 6 Non-scale ToC illustrating the relationship between nozzle downstream velocity, pressure drop and production rate

Fig. 7 shows that manufacturing cost and complexity of the mixing tube are determined by the length of the body. Increasing the length beyond five meters (5m) will cause difficulties in manufacturing, as the tools available at the current manufacturer would require the mixing tube to manufactured in two parts.

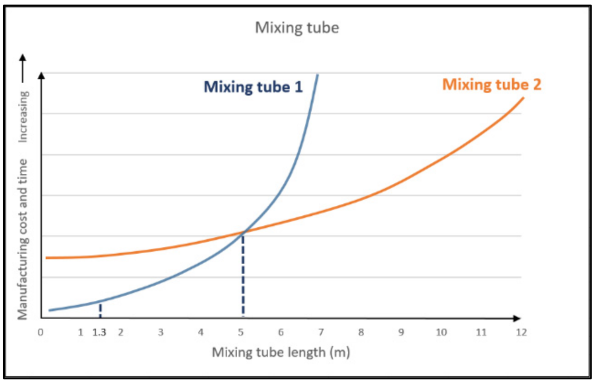


Fig. 7 Non-scale ToC illustrating the relationship between mixing tube length and its manufacturing cost and complexity

Finally, Fig. 8 illustrates the physics-knowledge of the body component. It is apparent that different designs of the LP inlet affect the HP/LP pressure ratio, allowing to obtain the desired discharge pressure with less pressure from LP. Thus, the design performance is increased. However, both manufacturing cost and complexity of the body increase significantly. Furthermore, the material type will affect its cost, manufacturability and durability through different carbon content levels and maximum allowable stress levels.

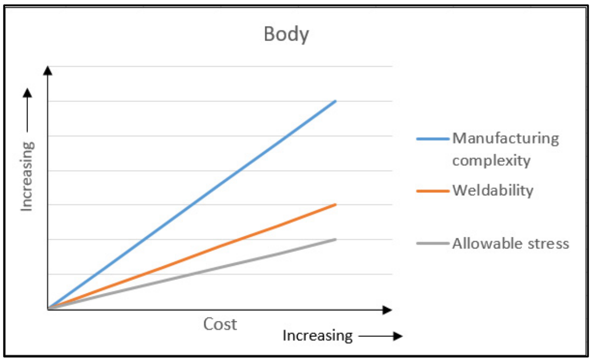


Fig. 8 Non-scale ToC illustrating the relationship between body cost and design parameters: manufacturing complexity, material weldability and allowable stress levels

Analysing these three non-scale physics-based ToCs for each component facilitated decision-making about the feasible solution for the mixing tube and body. Since the length of the mixing tube is required to be less than 5m in this case study, where the target value was 1.3m, design solution MT2 (Fig. 5) was eliminated. Regarding the body design, Fig. 8 shows that more complex manufacturing features will result in an increase of cost. Therefore, design B3 (Fig. 5) was removed from the design-set. Only one mixing tube (MT1) and two bodies (B1 and B2) remained in the design-set, as well as ten nozzle designs.

3.4. Compare and narrow down on component level

In order to evaluate the performance of nozzle designs, scaled ToCs needed to be generated. Data for the manufacturing cost and complexity was collected from the manufacturers. In addition, data about the nozzle downstream velocity was obtained from CFD (computational fluid dynamics) simulations. With the data, both the knowledge-based and the physics-based ToCs can be combined into only one graph, as shown in Fig. 9. This graph was used to compare different nozzle designs and to identify the feasible solutions. It is apparent that N3, N5, N6 and N8 (Fig. 5) have high manufacturing cost and complexity, while the velocity is even lower than the original design N1. Therefore, these four solutions were eliminated from the design-set. Although N7 shows a good performance in manufacturing cost and complexity, the velocity is lower than in any other design solution. Thus, N7 was also removed. N9 was another design solution that was eliminated, since its design performance was lower than N1. Following these decisions, N2, N4 and N10 are the remaining design solutions, as they have the potential for meeting the customer requirements and decision criteria.

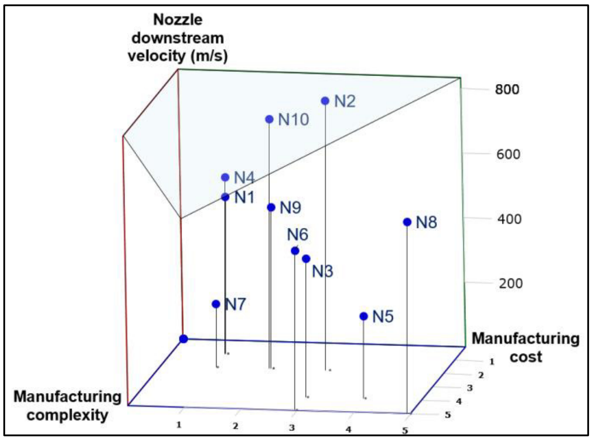


Fig. 9 Three-dimensional ToC used to compare and narrow down the nozzle design-set shown in Fig. 5

3.5. Compare and narrow down on system level

The new design-set consists of three nozzles, one mixing tube and two bodies. It is a result of comparing and narrowing down on the component level. As each component can form a system with each of the other components, there were six different design solutions in total. The design team evaluated these design combinations on the system level. To facilitate decision-making, three more ToCs were generated, for each decision criteria, with the design-set being:

1. N2+MT1+B1,
2. N2+MT1+B2,
3. N4+MT1+B1,
4. N4+MT1+B2,
5. N10+MT1+B1,
6. N10+MT1+B2.

It was found that although two designs (3 and 4) were performing well in manufacturability and cost, they delivered low design performance. For the rest of the system designs, the results were inversed. Therefore, the design team decided to generate a new trade-off curve which would illustrate the design performance from the discharge pressure aspect.

3.6. Identify the optimal design solution

A higher discharge pressure provides a higher production rate. The data for the discharge pressure was collected from the CFD system simulations, which are based on understanding the physical characteristics of the product. The data for manufacturing cost and complexity was collected from the manufacturer with a scale of 1 to 7, where 1 represents the lowest cost and degree of complexity, and 7 the highest. A new ToC was generated with the collected data, as shown in Fig. 10.

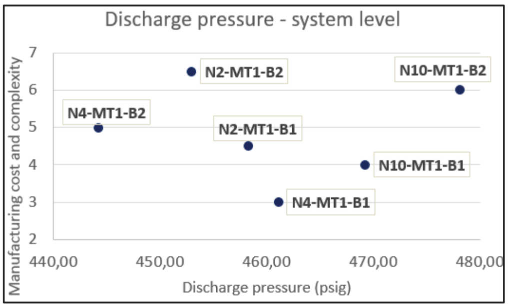


Fig. 10 Combination of knowledge-based and physics-based ToCs on the system level

As shown in Fig. 10, system designs with N10 are showing a promising performance in terms of all decision criteria. However, although design N10+MT1+B2 is the best solution regarding discharge pressure, manufacturing this product would be quite complex and costly. Therefore, the design team selected N10+MT1+B1 as the optimal design. It is shown in Fig. 11 and meets the all customer requirements.

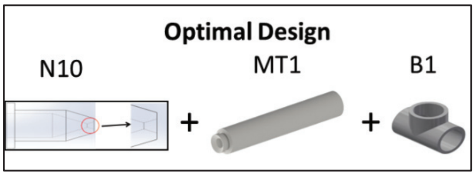


Fig. 11 The optimal design solution identified through the integrated use of ToCs within the SBCE process

4. Conclusions

In order to introduce innovative, high-quality products in a time and cost-efficient manner, companies need to improve the performance of their product development processes. Set-based concurrent engineering has the capability of addressing this issue only if the right knowledge environment is provided. Trade-off curves are effective tools to provide this environment through knowledge creation and visualisation. Therefore, in this paper, the integrated use of ToCs within the SBCE process model has been demonstrated in an industrial case study for a surface jet pump. Evaluating the set of 60 alternative design solutions using a traditional approach would have been very resource intensive. The application of knowledge-based and physics-based ToCs allowed the gradual narrowing down of the design-set until the optimal design solution was identified. Thus, it enabled a significant enhancement of the product development process by considering different design solutions in parallel. Additionally, generated trade-off curves saved a considerable amount of resources by providing sufficient knowledge for the designers to make their decisions. Furthermore, the need for prototyping was eliminated through the use of both knowledge-based and physics-based ToCs.

The proposed integrated approach can be implemented in developing a wide range of products, from simple to complex. This study is limited to a medium complexity product, a surface jet pump. A further study will be required to assess the effects of implementing the proposed approach in a more complex product, such as an aircraft jet engine.

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