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

Zehra C. Araci[a], Ahmed Al-Ashaab[a]*, Piotr W. Lasisz[a], Jakub W. Flisiak[a], Muhd I.I. Mohd Maulana[a], Najam Beg[b], Abdullah Rehman[b]

[a]*Cranfield University, College Road, Bedford MK43 0AH, United Kingdom*
[b]*Caltec Limited, Medway Court, Bedford MK43 0FQ, United Kingdom*

* Corresponding author. Tel.: +44-1234-750-111 x5622. *E-mail address:* a.al-ashaab@cranfield.ac.uk

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%.

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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.