Cost-Benefit Analysis – Requirements for the Evaluation of Self-Optimizing Systems

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Summary: Mechatronic systems are omnipresent. Mechatronic is characterized by the close interaction of mechanics, electrics/electronics, control and software engineering. To develop successful mechatronic systems economic aspects need to be evaluated, e.g. by Target Costing, Value Engineering or Economic Value Analysis. More often, the choice among alternative solutions of systems involves trade-offs between functional performance and costs. For the decision making in the early design phase the balance of benefits, obtained from systems performance, and of costs of systems realization and operation is important. The conceivable development of information and communication technology enables technical systems with inherent partial intelligence. We refer to this by using the term self-optimization. Self-optimizing systems react autonomously and flexibly on changing environmental conditions. They are able to learn and optimize their behavior during operation. The analysis of costs and benefits of self-optimizing systems places new requirements that cannot be fulfilled adequately by the existing methods. This contribution depicts the requirements on a cost-benefit analysis for self-optimizing systems in the conceptual design and opposes the requirements with the state of the art to figure out the shortcomings of the existing methods.

Keywords: Self-Optimizing Systems, Design Methods, Economics, Cost-Benefit Analysis.

1. Introduction

Mechatronic is characterized by the close interaction of mechanics, electrics/electronics, control and software engineering. The conceivable development of communication and information technologies opens up fascinating perspectives for future systems. The integration of cognitive functions into mechatronic systems enables systems with inherent partial intelligence. These systems are referred to as self-optimizing (s.o.) systems. The paradigm of self-optimization is the research subject of the Collaborative Research Centre (CRC) 614 “Self-Optimizing Concepts and Structures in Mechanical Engineering” of the University of Paderborn. Self-optimization describes the endogenous adaption of the system´s objectives due to changing operation conditions and the resulting autonomous adjustment of system’s parameters or system structure and consequently of the system´s behavior. The key aspects and the mode of operation of a s.o. system are illustrated in figure 1. The CRC 614 provides the foundation for the development of s.o. systems. Previous work has shown, that the design of such systems is challenging [1]. The increasing complexity of functionality and structure raises the requirements for the development and analysis of s.o. systems. Those new requirements cannot be satisfied by established design methodologies of conventional mechanical engineering [2] and methodologies for mechatronic systems [3]. Therefore the CRC 614 developed a new design methodology [4].

More often, the choice among alternative solutions of systems involves trade-offs between functional performance and costs. For the decision making in the early design phase the balance of benefits, obtained from systems performance, and of costs of systems realization and operation is important. To ensure the development of successful systems economic aspects need to be evaluated to select the most promising alternative solution [5]. For this the costs and benefits of the alternative solution have to be taken into account. Although not only the development and production costs need to be estimated, but also the lifecycle costs for the customer. Lifecycle costs consist of initial costs, one-time costs, operating costs, maintenance costs and other costs, e.g. taxes [6]. For the evaluation of costs numerous approaches exist. Due to the autonomous behaviour the analysis of the benefit for s.o. systems is much more difficult than for mechatronic systems. We differentiate between three benefit categories: direct, indirect and strategic benefit. Direct benefit results from an increased functionality of the system itself. Indirect benefit results from positive functional effects of the system to its environment, which does not correspond to the original purpose of the system, e.g. CO_2 reduction. Strategic benefit is divided into external strategic benefit, e.g. market potential and internal strategic benefit, such as know-how potential [7]. These benefit categories need to be considered in the analysis.

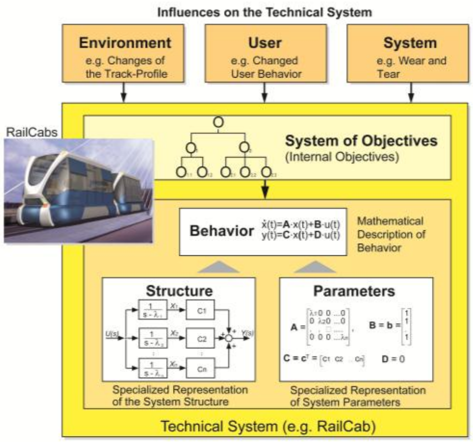

Figure 1. Aspects of self-optimizing systems [1].

The analysis of s.o. systems places new requirements on a cost-benefit analysis in the conceptual design. This contribution depicts these requirements and opposes them with the state of the art for mechatronic systems.

In section 2 the development process for s.o. systems will be introduced and the evaluation points identified. Based on this we will propose requirements for the cost-benefit analysis of s.o.

systems. Afterwards those requirements are opposed with the state of the art to identify the need for action. Finally we will give a short outlook on the further procedure.

2. Cost-Benefit Analysis of Self-Optimizing Systems in the Conceptual Design

The basic procedure in the conceptual design phase for s.o. systems is divided into sub phases: Planning and clarifying the task, conceptual design on the system's level, conceptual design on sub-system's level and integration of the concept. To reduce the complexity of the development of s.o. systems, within the conceptual design, a new specification technique to describe the principle solution of s.o. systems was developed within the CRC 614 [4]. It describes not only the physical, but also the logical operating characteristics of the system. The description of the principle solution is divided into several aspects (figure 2). The principle solution is concretized during the conceptual design.

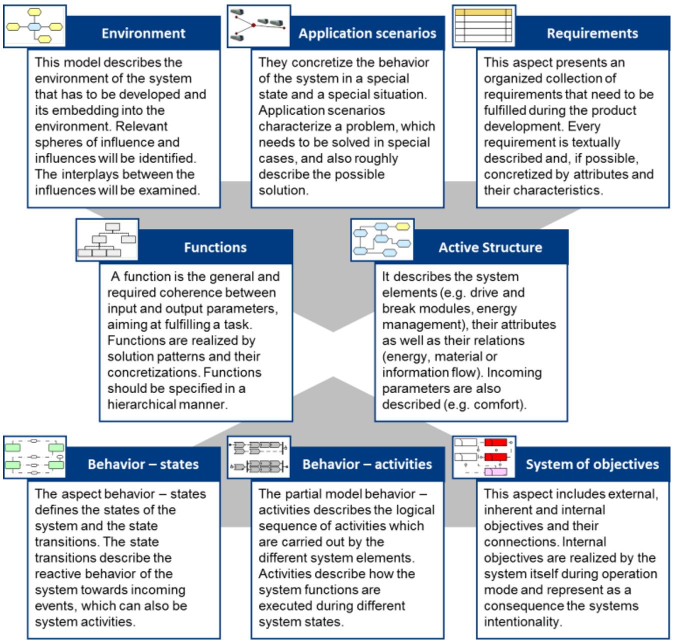

Figure 2. Short description of the used specification technique [4].

The functional hierarchy is an important intermediate result during the conceptual design phase of mechatronic and s.o. systems, derived primarily from the functional requirements. The sub-functions at the bottom are the initial point for the search of suitable solutions from any participating domain. The next step is to combine the solutions to alternative solutions. The alternative solutions need to be evaluated to select the most promising solution. For this solution the aspects active structure and behavior are specified. Unless the need for self-optimization is not indicated directly from the systems requirements the presented approach is similar for mechatronic systems. The system has potential for the use of self-optimization, if conflicts between the system's objectives can be identified [8]. To resolve these conflicts cognitive functions are integrated and a s.o. alternative solution developed [9]. Finally the mechatronic and s.o. alternative solutions are compared and the most promising is selected. Consequently there are two evaluation points in the phases conceptual design on system's level and conceptual design on sub-system`s level that need to be supported by the cost-benefit analysis. The first evaluation is after the step "Combination to alternative solutions" and the second during the step "Systems Analysis".

2.1. Requirements for the Analysis of Costs and Benefits of Self-Optimizing Systems

The previous sections showed the specialties of s.o. systems in comparison to mechatronic systems. Due to these specialties, requirements on the cost-benefit analysis for s.o. systems in the conceptual design result. These are as follows:

1. **Support of the Conceptual Design**: The analysis has to be based on the principle solution.
2. **Scalability**: The method has to be adaptable for different stages of concretization of the principle solution.
3. **Selection of Alternative Solutions**: The results of the method have to provide decision support for the selection of the promising alternative solution.
4. **Enable Economic Analysis**: The method is intended to support both cost and benefit analysis.
5. **Consideration of the System's Operation**: The method has to consider the costs and benefits resulting from the endogenous adaption of the system´s objectives due to changing operation conditions and the resulting autonomous adjustment of the system´s behavior during operation of s.o. systems.
6. **Monetary Quantification**: The method has to allow the monetary quantification of costs and benefit of the system.
7. **Comparability**: The method has to support the comparison of mechatronic and s.o. solutions.
8. **Extensibility**: The method has to be extensible to use it for the analysis of the solutions during the phases design and development.
9. **Manageability**: The effort for the use of the method has to be manageable, so that it can be used even for very complex systems in an acceptable time frame.
10. **Comprehensive Evaluation of Benefits**: The method has to consider the three benefit categories for the analysis: direct, indirect and strategic benefit.
11. **Comprehensive Evaluation of Costs**: The method has to ensure the cost estimation over the total system's lifecycle.

2.2. State of the art of cost-benefit analysis

The classical development process for mechanical products provides successively the steps "Generation of Alternative Solutions"; "Analysis", "Evaluation" and "Selection of the Promising Solution" [2]. For the analysis and evaluation of the alternative mechatronic solutions in the conceptual design the following proven methods can be used:

Target Costing is an interdisciplinary, team- and market-oriented approach for planning and controlling costs in the early design phase. It specifically aims to meet the needs of the market and customers with the system to be developed [10].

Value Engineering is a systematic approach to improve the value of products by using an examination of the systems functionality. Primary tenet of value engineering is to improve the value without reducing the basic functions of the system [11].

Benchmarking is a management instrument to compare the own product with competitive ones [12].

Lifecycle Cost Estimation is a method to analyze the costs of a product over the lifecycle, from development to disposal [6].

In the **Economic Value Analysis** [13] the overall benefit of the alternative solution results from the sum of the weighted partial benefit of the alternative solution [2]. It can be used computer-based and allows a sensitivity analysis of the results [6].

Technical Economical Evaluation introduces no hierarchical order for evaluation criteria, but derives a list of them from minimum demands and wishes and also from general technical properties. It tries to dispense with weightings and instead relies on evaluation criteria of approximately equal importance [14].

ABC Analysis allows the identification of those functions that provide the greatest benefit for customers and thus supports the resource planning for the design and development phase [15].

Simple Point Evaluation performs the evaluation of product ideas and gives the possibility of alternatives comparison by evaluating the main functions of the system [15].

Weighted Point Evaluation is the extension of the simple point evaluation. The evaluated functions are weighted due to the importance for the customer [15].

The analysis of the current state of the art shows that there are a lot of approaches for the analysis of costs and benefits of mechatronic systems. One part of the approaches focuses on the evaluation of costs. Other approaches give priority to both costs and benefits. Figure 3 shows in detail how far the analyzed approaches fulfill the requirements stated in section 2.1 on a cost-benefit analysis for s.o. systems. All analyzed approaches fulfill only a single part of the requirements. This applies especially for the aspects comparability and the consideration of the system's operation. Furthermore, the analyzed approaches do not support the evaluation based on the aspects of the principle solution.

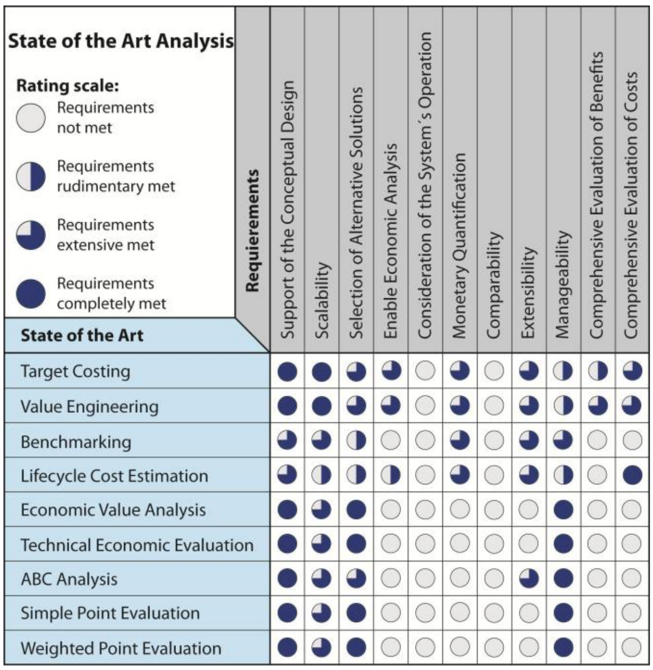

Figure 3. Analysis of the state of the art.

3. Further Procedure

A cost-benefit analysis in the conceptual design is necessary to ensure the development of a successful s.o. system. S.o. systems provide new requirements on the evaluation of costs and benefits. Especially the analysis of the benefit is not supported adequately. We develop a cost-benefit analysis that considers the benefits resulting from the autonomous systems adaption during the operation and the costs of self-optimization sufficiently. Therefore on the one hand we will provide a method to identify the benefit within the three benefit categories [7] for the s.o. system over the system's lifecycle, especially in the systems operation. On the other hand a method will be provided to analyze the costs for the implementation and operation of self-optimization. Both variables will be expressed in monetary values. The resulting cost-benefit analysis has to be usable for both mechatronic and s.o. systems to enable a comparison between them.

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