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A customer requirement driven framework for design synthesis - applied to a washing machine

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Abstract: In order to maximize the success of a product, the customers' wishes need to be integrated into the entire product design process. The design of a mechatronic system can be divided in a 3 different phases, requirements engineering, architectural design and detailed design. During the requirement phase, customers needs are translated into engineering characteristics. In the architectural phase, the topology, consisting of the number and type of components, as well as some key properties (size, material) of the different components, is chosen. This phase has a major impact on the final product performance.
Since (mechatronic) products need to meet an ever increasing number of performance specifications and constraints, recently computational design synthesis approaches have been developed to support design engineers. These types of methods use computational power and computer models to search the design space in an automatic way. However, as these methods focus entirely on maximizing the functional performance, the customers' actual wishes and needs may slip to the background.
This article presents a novel computational design synthesis approach which integrates design space exploration and Quality Function Deployment during the architectural design phase. The proposed method allows to generate architectures that maximize customer satisfaction. The effectiveness is illustrated by an industrial case study: the design of the mechanical architecture for a washing machine.

Keywords: QFD, House of Quality, Formal Modeling, Computational Design Synthesis, Architectural Design

1. INTRODUCTION

Customer satisfaction is one of the most important aspects in product design, determining a companies economic success. In order to meet the customers' wishes in the best possible way, their demands need to be systematically integrated into the product design process. This is especially true in the home-appliance industry, where competition is hard, price-levels are continuously attacked while at the same time new technology keeps driving capabilities forward. One example is the washing machine, a well-known home appliance which has existed for several decades.

According to Berliner and Brimson (1988), design decisions made in the early design stages have a major influence on the characteristics of the final design. An important stage is the architectural design, in which the architecture of the new system is synthesized, fixing the components used and their key properties. Many researchers, such as Wyatt et al. (2012) and Lin et al. (2009), have explored design space exploration (DSE) tools to automate this stage and generate novel architectures. This is achieved by formulating the architectural design stage as a numerical optimization problem and translating it to an appropriate solver. However, the value of the designs generated are determined by the objectives and constraints used in the optimization. For a manufacturer to gain an edge through the use of DSE, the optimization problem being solved needs to be directly related the customer needs.

According to Chan and Wu (2002), Quality Function Deployment (QFD) is an overall approach for translating the qualitative customer requirements into the appropriate quantitative technical requirements for each stage of product development and production. The results of such a QFD approach can be used within the architectural design stage to evaluate and compare different architectures in order to select those that maximize customer satisfaction.

In this work, the authors show the integration of an existing framework for DSE, as described by Berx et al. (2014), with a QFD analysis. The resulting approach allows to accelerate the architectural design stage, while ensuring the integration of the customer requirements, resulting in designs that maximize customer satisfaction. This approach is applied to a washing machine use case. Section 2 shortly describes related research in the areas of washing machine design, QFD and DSE. Next, sections 3, 4 and 5 respectively describe the application of QFD to the

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design of a washing machine, the analysis of the design problem and the resulting optimization problem. Section 6 compares the different generated washing machine architectures. Finally, section 7 presents some conclusions and directions for future research.

2. RELATED WORK

2.1 Washing machine design

According to Nygårds and Berbyuk (2014), washing machine research focuses on reducing energy consumption, increasing capacity and preventing walking (the machine moving from its position due to the unbalance forces during drum rotation).

In recent years, the washing machine is seen more as a part of a washing and drying system, increasing the importance of the drying process. The more water that can be extracted through spinning of the laundry, the less has to be removed by other means such as heating which consumes of lot of energy. This causes the spinning performance to be taken more into consideration when the energy consumption grading is determined (see Energy Star (2013)), which makes increasing the spinning speed a new driving force towards improving this rating. However, increasing the spinning speed also amplifies the undesired vibrations and noise, which causes discomfort to the user and reduces the lifetime and reliability of operation of the machine.

Increasing capacity is a second focus point in washing machine research. Customers want to wash a bigger amount of laundry per cycle. More laundry per cycle requires a bigger drum diameter and causes a higher amount of (probably eccentric) spinning mass which in turn results in higher dynamic load imbalance during operation. This causes unwanted side-effects, such as vibrations and noise at high spin revolutions up to "walking" washing machines.

This walking behavior is an important topic in washing machine research. The current trend is towards lightweight plastic and composite components. However, the reduction of mass associated with these changes increases the possibility that a washing machine will walk. The topic of walking is treated with the creation of static design conditions to be fulfilled in order to avoid this undesired behavior.

Some authors have studied the impact of some of the design decisions made during the architectural design phase on these different aspects. Conrad and Soedel (1995) presents a simple model for a comparison of the walking behavior of top- and front-loading machines. In Nygårds and Berbyuk (2014) a multi-body model of the washing machine is created. This model is used to optimize the suspension system with respect to vibration output. To the authors best knowledge, no work exists on a more complete optimization of the washing machine architecture taking into account all the customer requirements described above.

2.2 Design Space Exploration

According to Saxena and Karsai (2010), a design space is the scope of all possible design choices and design space exploration (DSE) is the process of automatically searching through this design space to find specific design alternatives that satisfy various design constraints and are "best" with respect to one or more objective functions. DSE has been successfully applied within many domains such as software deployment on a distributed set of ECUs (Denil (2013)), software product line configuration (Saxena and Karsai (2010)), electrical circuit design (Koza (2002)) and mechanical system design (Wyatt et al. (2012)).

DSE techniques can be applied during different stages of the design. Research areas range from the conceptual design stage (Helms et al. (2009)), over the architectural design stage (our research, and others), into the detailed design stage, where typically only parametric optimization is applied (Shah et al. (2012)).

These DSE frameworks all contain similar steps: (i) represent the design space, (ii) evaluate design alternatives and (iii) explore the design space using guidance algorithms to find feasible, near-optimal and optimal designs.

When using DSE in the architectural design phase, the different architectures generated are usually evaluated and compared through the use of metrics (Wyatt et al. (2012)). However, since these metrics are the designers' interpretation of an architectures optimality, the resulting designs do not necessarily maximize customer satisfaction.

2.3 QFD

Quality Function Deployment (QFD) is a matrix-based approach that aims to consider the customer wishes throughout the entire product design process. QFD was developed and first applied in Japan in late 60's. Akao (1972) was the first article on "Quality Deployment" to present the ideas, developments and findings. After ten years of ongoing development of QFD in Japan, King (1987), Hauser and Clausing (1988) were the first to learn of QFD in the US according to Chan and Wu (2002).

One widespread approach to QFD, introduced by the American Supplier Institue (ASI) (see ASI (2016)) consists of only four matrices as shown in Figure 1. The matrices are called Houses of Quality (HoQ). Compared to the Japanese and Kings approaches which utilizes up to 30 matrices, the ASI-approach is easier to use.

The typical ASI-approach of QFD centers around four design stages or Houses of Quality:

(1) Product Planning (HoQ-1) is used to translate qualitative customer requirements (CRs) to measurable engineering characteristics (ECs);

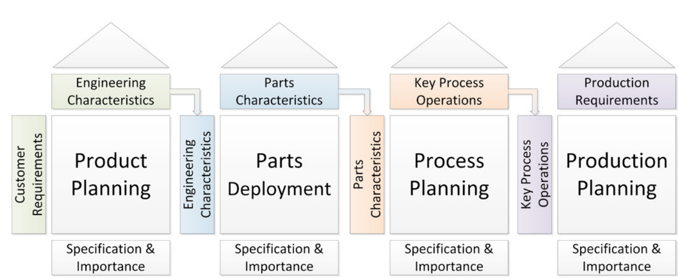

Fig. 1. Four phase QFD approach by ASI