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Optimal Decomposition of High-Dimensional Solution Spaces for Chassis Design

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Preface

This thesis is based on the results obtained during my time as a PhD student from 2013 to 2016. During those years I was involved in a joint research project between the Technical University Munich (TUM) and the BMW Group being simultaneously a member of the *TUM Graduate School* and the *BMW ProMotion Program* in Munich. At the TUM, I participated mainly in the activities of the research group of Prof. Dr.-Ing. habil. Fabian Duddeck, Associate Professorship of Computational Mechanics while at BMW, I worked in the development department for driving dynamics, preliminary design.

I would like to express my deep gratitude to my supervising Professor Fabian Duddeck for giving me the opportunity to join his research group, providing me support whenever necessary and enriching my work with a critical review and fruitful discussions.

I would like to thank Prof. Dr. Markus Zimmermann for supervising me at BMW. I particularly appreciate that he gave me the opportunity to do research in an industrial environment, that he shared his expertise in Solution Spaces, in which he has done extensive research in recent years. Furthermore, I would like to point out the numerous valuable discussions we had and still have together.

I also would like to thank Prof. Dr. rer. nat. Matthias Gerdts, Universität der Bundeswehr München, for inspiring discussions and technical support as well as for agreeing to be part of the committee.

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I would like to thank my family and friends for proof reading and their valuable comments, and would like to express my deepest gratitude to my father, who enriched this thesis with his admirable sketches.

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Stefan Erschen
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Abstract

Today, one challenge in vehicle development is dealing with increased complexity, i.a. as a consequence of a *large number of interacting components and subsystems*, *many requirements*, often in conflict to each other, and a *large variety of vehicles* that must be considered. In general, complexity leads to time-consuming and hence cost-intensive development processes. In contrast, an increasing number of competitors require efficient product development in terms of time and cost.

Design methodologies such as concurrent engineering and set-based design exist to handle complex design problems more efficiently. One aspect of *concurrent engineering* is that components and subsystems are developed simultaneously rather than subsequently. This potentially reduces the overall development time, however, due to interactions among the components and subsystems, concurrent engineering increases uncertainties due to lack of knowledge. The idea of *set-based design* is to consider a set of permissible designs, which is narrowed throughout the development when more information, e.g. precise customer needs, cost, manufacturability, etc. is available. Although, this requires more effort in early development stages, it minimizes necessary iteration loops due to lack of knowledge and becomes more efficient overall compared to design strategies where one single design is considered only. Set-based design in conjunction with concurrent engineering is a powerful combination of two design strategies, compensating the shortcomings of the individual methodologies and enabling efficient development processes.

Recently, many set-based design approaches, particularly relying on numerical simulation, were proposed to increase the efficiency of development processes. One approach is based on the computation of box-shaped Solution Spaces, representing permissible design alternatives that satisfy all specified requirements. Box-shaped Solution Spaces are compatible to concurrent engineering, since requirements on the system are formulated as independent requirements on components and subsystems, which can be developed in detail independently and simultaneously as a result.

This thesis proposes improved approaches to compute Solution Spaces, such that uncertainties due to lack of knowledge are taken into account at its best, such that the result is compatible to concurrent engineering and such that the approaches are applicable to development problems particularly in chassis design.

Firstly, a gradient-based approach is proposed for optimizing the number of design alternatives via a search of box-shaped Solution Spaces with maximum volume. The underlying optimization problem is analyzed, and the approach is validated via analytic test problems. The results are compared to an existing technique using a stochastic Solution Space algorithm.

Motivated by the fact that box-shaped Solution Spaces are possibly sub-optimal to represent the whole set of permissible designs, approaches based on a two-dimensional decomposition of high-dimensional Solution Spaces are introduced. This enables an improved handling of uncertainties in the early development phase. Two approaches are presented and the underlying optimization problems are analyzed and discussed. Both approaches are validated again by analytic test problems.

Furthermore, the approaches are compared in terms of their numerical complexity, and the advantages and disadvantages of box-shaped Solution Spaces compared to a two-dimensional decomposition of Solution Spaces are discussed.

Finally, the applicability of the approaches is demonstrated by industrial examples in the field of chassis design. The examples comprise the development of single vehicles as well as the development of a set of vehicles, where the components need to be designed such that requirements on the driving dynamical behavior are satisfied.

Contents