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A knowledge-based master model approach exemplified with jet engine structural design

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ABSTRACT

Successful product development requires the consideration of multiple engineering disciplines and the quantification of tradeoffs among conflicting objectives from the very early design phases. The single-largest challenge to do so is the lack of detailed design information. A possible remedy of this issue is knowledge-based engineering. This paper presents a knowledge-based master model approach that enables the management of concurrent design and analysis models within different engineering disciplines in relation to the same governing product definition. The approach is exemplified on an early phase structural design of a turbo-fan jet engine. The model allows geometric-, structural mechanics- and rotor-dynamic- models to be concurrently integrated into a multi-disciplinary design and optimization loop.

1. Introduction

Design decisions made in the early phases of product development (PD) have a significant impact on a product's life cycle. Knowledge-based engineering design methods have been used for decades in industry; however, the pertinent literature body is relatively small [1]. This topic is gaining renewed interest because the maturation of computer-aided modeling techniques enables the consideration of multidisciplinary tradeoffs early in the design phase. Early phase engineering design decisions typically concern reducing mass, fuel consumption, manufacturing costs and environmental impact while increasing performance. As a consequence, effective early design requires modeling approaches that can predict adequately all these quantities of interest by accounting for their interactions by coordinating multidisciplinary analyses. The increased adoption of multidisciplinary optimization techniques requires automation of both model generation and evaluation. The overarching objective of this paper is to present a methodology that enables the integration of multidisciplinary analysis and simulation techniques that revolve around a single master model. While systems engineering methods are supposed to tackle such design problems systematically [2], updating models for each of the many design changes occurring in early phases is a bottleneck. A tighter coupling of the various descriptions of the product and its environment is thus required. Using virtual product modeling techniques, such details can be generated by creating conceptual design solutions with a greater resolution.

In the manufacturing industry, virtual product models are used to predict life-cycle effects of alternative designs. Engineering disciplines usually use their own domain models for early assessments. Domain model examples include structural dynamics, aerodynamics and thermodynamics. Even within a single company, such domain models can vary significantly at different system levels with respect to modeling approach and fidelity. Different domain models are being modified concurrently without coordination. Restrictions due to the complexity of performing updates risk locking the design into suboptimal solutions.

Component manufacturers (suppliers) strive continuously to integrate updated information from original equipment manufacturers (OEMs) into their models. To that end, there is a need for

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models that link system-level product definitions to component-level design and analysis activities. One way of addressing this challenge is to create master models (MMs) that integrate different models automatically [3]. Changes in the MM propagate to all linked models. Knowledge-based engineering (KBE) enables the creation of rule-based computer-aided design (CAD) models with geometrical and topological flexibility as well as design automation capabilities.

Previous work has demonstrated the potential of KBE for building and managing master models [5–7]. This paper demonstrates a detailed application of KBE tools and how the MM generates the necessary analysis models, and exemplifies this approach for structural design of jet engines.

2. Background

Knowledge-based engineering stems from knowledge-based systems [8] and LaCourse claims that KBE was coined at the release of the CAD software iCAD [9]. Stokes defines KBE more generally as "the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way" [10], while others describe it more connected to CAD. La Rocca classifies KBE as artificial intelligence (AI) and CAD [5], while Kuhn et al. place it on the crossroads of AI, CAD and programming [11], although KBE models tend to be based more on explicit rules than on computational intelligence. The core is about creating a generative model ([12]) that can generate engineering items such as geometry, reports, bills of materials, or finite element models [13]. By using rules, geometry objects can be generated and manipulated in a way beyond traditional parametric models. Radical topological changes, e.g. changing a cylinder into a rectangular prism, are possible. KBE applications were found useful for routine engineering tasks [12,14]. During the last decade, the major CAD/PLM (product lifecycle management) software vendors have implemented KBE modeling capabilities (e.g., Siemens PLM software NX and Dassault Systemes CATIA).

Verhagen et al. [1] identified that reported applications have been largely developed on a seemingly ad-hoc manner, and that there is a lack of methodological support in practice, where structured development approaches, such as MOKA (Managing Engineering Knowledge: Methodology for Knowledge Based Engineering) [10], have not been widely adopted, possibly since such tools address complete KBE system design which have often been considered to be too rigid in practical applications.

There exist numerous approaches where the challenge of integrating CAD models with computer-aided engineering (CAE) models is targeted. Lee presented a CAD-CAE integration strategy for feature-based design [15]. The strategy is based on a MM that creates the required CAD and CAE models. CAD model creation is done interactively with the user, while the abstraction and dimensional functions are semi-automated. Since the Lee framework is not fully automated, further work is required to use it for numerical optimization. Hong-Seok and Phuong integrated CAD and CAE using scripts, programming languages, application programming interfaces and meta-modeling to perform structural optimization [16]. Their approach is limited to traditional parametric capabilities; more radical geometry changes, permitted by KBE, are absent.

Liu et al. presents a framework for multidisciplinary optimization (MDO) of complex engineering systems focusing on a web-based utilization of agents and ontologies to enable cooperation in geographically-dispersed teams using heterogeneous platforms with different analysis tools [17]. However, they do not report details on how to handle more radical geometry changes automatically, which is critical in early design. Ledermann et al. present two dynamic CAD concepts for generating repetitive CAD structures to be used in optimization [18]. The concepts look promising although the paper is quite applied and focused on CATIA V5. Amadori et al. further develop the ideas of Lederman et al. and focus more on the geometry generation process for MDO [21]. High-level CAD templates are described and exemplified in several CATIA V5 applications and the notion of geometry flexibility and robustness is discussed. La Rocca and van Tooren describe the idea of a multi-model generator that can generate a number of different analysis models [4]. The governing logic for this model generation is described as rules residing in high-level primitives geometry, similar to the CAD templates of [18,21], and so-called reports. These reports are able to distil the parts of the product model that are needed by the analysis tools. However, examples of this governing logic are not given.

Despite the relative success of KBE approaches, the design methodology of using a governing master model is not well established. In particular, there are no detailed reports or examples on how analysis model generation can be accomplished. Best practices that maximize the use of software functionality offered by vendors implies a risk over time, where methodologies or rule dependencies may become obsolete as new software tools and versions are launched. A system-independent, yet system-implementable, design logic is needed. Detailing the actual constituents of the knowledge-based master model (KBMM) is of primary interest.

3. The knowledge-based master model approach

The underlying principle of the approach presented in this paper, is that several different engineering disciplinary design and analysis skills in parallel contribute to the understanding of the same design definition. The task is to eliminate sequential dependencies by enabling multiple disciplines to concurrently operate on the same master definition. This master definition needs to represent the common governing information for all necessary analyses.

From an engineering design perspective, the design problem needs to be defined upfront, including which disciplinary analyses and tools that need to be considered in the design loop. To be efficient, there is a need to automate each step of the design loop

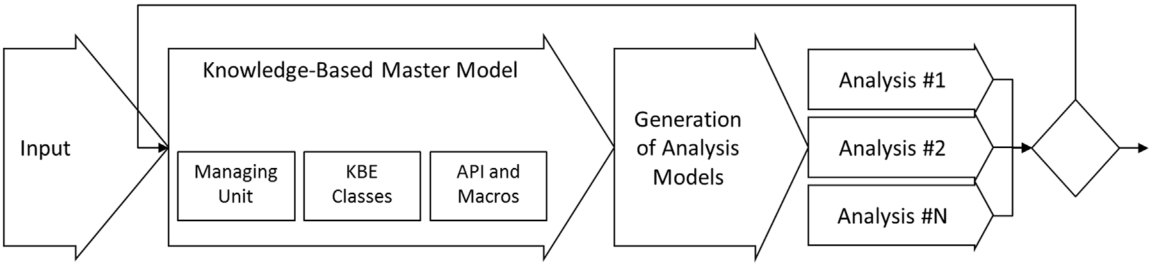

Fig. 1. Overview of the knowledge-based master model (KBMM).