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Estimation of aircraft component production cost using knowledge based engineering techniques

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ABSTRACT

A comprehensive method is presented to estimate aircraft component production costs using Knowledge Based Engineering (KBE) techniques. A suite of parametrical cost estimation blocks are treated as Cost Primitives (CPs), which contain attributes such as cost types, cost driving parameters, and cost estimation relationships. A CP is associated with a parameterized geometry and a set of specific design parameters including part/assembly types, materials and production methods. Production cost is estimated by aggregating the cost of different CPs within a tree structure integrating both product breakdown and cost breakdown structures. The cost analysis tool is integrated into a KBE application by building Capability Modules (CMs), which provide manufacturable geometric representations for cost estimation and can be used to summarize output reports for further optimization. Case studies concerning stiffened panels are carried out, verifying the accuracy of the cost estimation method and illustrating the applicability of this method together with the integrated KBE application for various aircraft components. The main contribution of this research is automating the cost integration in the design process to improve the fidelity, repeatability and traceability of cost analysis.

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1. Introduction

In aviation industry, production cost estimation is of significant importance in early design stage. A total of 85% of the overall Life Cycle Cost (LCC) is determined by design choices at the end of the preliminary design stage, while 95% of the LCC is locked at the end of the detailed design [1]. Aircraft production cost accounts for around 32% of the LCC [2]. Moreover, production cost is tightly related to acquisition cost, which in turn is linked with operating cost. When combining these statistics, the importance of production cost estimation is evident.

In response to this realization, research into production cost estimation and its corresponding application development has progressed significantly. A major theme in research is integration. Integrating production cost into models for LCC estimation has been intensively studied [3,4]. Furthermore, integrating new technologies, for instance by modeling and estimating production cost of composite products, has seen significant interest both in and outside of the aerospace domain [5,6]. Over the past decades, a trend in aerospace engineering is to integrate component conceptual design and cost analysis into one synthetic system, where the material, manufacturing and cost properties can be considered simultaneously in the early stages of design. Moreover, design and optimization studies including cost influence can also be performed within such systems. A group of researchers, including Kundu et al. [7], Price et al. [8], Curran et al. [9], Castagne et al. [10], and Early et al. [11], has developed a generic cost estimation tool by integrating cost into design, multidisciplinary optimization and system engineering. Van der Laan et al. [12] have integrated friction stir welding into a multidisciplinary aerospace system called the Design and Engineering Engine (DEE), building a process based model to compare the efficiency of friction stir welding and riveting process costs. The detailed integration process using Knowledge Based Engineering (KBE) techniques is further elaborated [13]. Another cost estimation tool has been developed by Scanlan et al. [14], who have emphasized cost estimation utilizing modular library elements and CAD-cost integration for design optimization automation. An architecture of a KBE application has been proposed by Choi et al. [15], where the interaction of the Knowledge Base (KB) and cost estimation is mainly discussed. Kaufmann et al. [16,17] have investigated cost/weight optimization by adopting commercial software packages, *viz.* SEER for cost estimation and ABAQUS for structure and weight analyses.

Although a number of attempts have been made to develop advanced costing approaches within the early design process, most of them suffer from the following issues:

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- **Loose geometry-cost coupling leads to rough estimates**: Cost estimations using parametric calculation methods often employ geometric attributes as the cost driving parameters, which requires a tight connection between geometry and cost to improve the accuracy [8,13,18–20].
- **Processing cost estimation is a labor intensive and time consuming task**: Data and calculations used for cost analysis are mostly stored in extensive spreadsheets; often, a spreadsheet application is used to facilitate cost calculations [14]. In this way, a significant amount of data needs to be imported manually and the knowledge of calculation is only available for the cost engineers who developed the spreadsheets [21].
- **The fidelity level of the cost estimation is restricted by specific design phases**: In the conceptual design stage, limited data are available for cost estimation. Besides, there is a lack of communication among cost engineers, manufacturers and designers in practice. Accordingly, the fidelity level of the analysis is depressed.
- **The reusability of the cost estimation is limited when design changes**: Some models incorporate fixed production processes for cost estimation. When the design changes, e.g. changes of geometric sizes and material types, the production process will be updated correspondingly. In such cases, the cost estimation model may not be applicable any more.
- **The traceability of the cost estimation is low due to vague connection between product and the evaluated cost**: The link between cost breakdown and product breakdown, which constitutes the core relation between design and cost, is typically not clearly defined and implemented [22]. Consequently, a distribution of the estimated costs on specific product structures is often not available.

In response to the aforementioned shortcomings, this paper introduces a comprehensive method to estimate aircraft component production cost using KBE techniques. By introducing a suite of parametrical cost estimation blocks, a generically applicable and automated cost estimation capability has been developed. The performance of this method is further verified and validated by a case study. This paper is consequently arranged as follows: in Section 2, the theory and principles of current KBE-assisted design and disciplinary performance analyses are introduced. Research on aircraft component cost estimation is reviewed and categorized. Those are then extended to include KBE-assisted cost analysis in Section 3, in which methodologies of KBE techniques supporting design and cost analysis are outlined. Section 4 presents a practical application of integrated cost analysis concerning the conceptual design of a stiffened panel. The verification and validation of the results are presented in Section 5. This is followed by discussions and conclusions in terms of the potential contributions of the proposed cost application in Section 6.

2. State of the art

According to the previously introduced problem statement, two main topics in literature are considered: (1) the use of KBE to support design integration and performance analysis and (2) cost estimation method for aircraft components.

2.1. Principles of Knowledge Based Engineering assisted design integration and performance analysis

A prevalent definition of KBE emphasizes ‘the capture and systematic reuse of the product and process engineering knowledge’ to automate ‘repetitive and noncreative design tasks’ and to support ‘multidisciplinary design optimization in all phases of the design process’. It is employed as an assistant to ‘realize an efficient and economic product development process’ [2]. The concept of KBE has been introduced after the integration of Expert Systems and Computer Aided Design (CAD) in the mid-1980s [23]. A more systematic approach for KBE system development has been proposed in the European project MOKA (Methodology and tools Oriented to Knowledge-based engineering Applications), resulting in the initial version of the KBE system life cycle and MOKA methodology proposed around the year 2000 [24,25]. A comprehensive report of the MOKA project has been documented by Stokes [26], which illustrates knowledge representation and management techniques, KBE life cycle identification and automatic code generation methodologies. Simultaneously, KBE applications integrated into product design and development have been generated by Chapman and Pinfold [27,28].

Based on the MOKA approach and examples of successful KBE applications in the aerospace domain [29,30], guidelines for aircraft component KBE application development can be summarized as follows: Prior to the actual development, the research group verifies the KBE applicability for the application case and determines policies of the application development in the company. The company can be either Original Equipment Manufacturers (OEMs) or Small and Medium sized Enterprises (SMEs). Afterward, technical development steps are taken based on the KBE life cycle. ***Firstly***, a domain KB should be developed by capturing and modeling the product and process knowledge, for instance in Unified Modelling Language (UML) or a UML-based visual modeling language. ***Secondly***, a KB management tool is needed to store, analyze, publish and maintain the product and process knowledge. The KB management tool can be separated from the design and analysis tool, but it can also be integrated. Some applications have been developed by featuring an embedded KB and related management within the design and analysis tool for simplification and convenience [2]. ***Thirdly***, a step of mapping the knowledge from the KB to the design and analysis process is necessary. This involves activities such as building data transmission between KB management platform to the design and analysis platform. The ***fourth*** step is to identify the design and analysis tasks and automate the process using the mapped knowledge and inference mechanisms. The KBE techniques employed in this step for performance design integration and disciplinary performance analysis are summarized in Sections 2.1.1 and 2.1.2. Once the KBE application is developed, final deployment to end users can be accomplished.

2.1.1. Knowledge Based Engineering assisted performance and design integration

In order to fulfill the requirements of design for performance, disciplinary analyses are carried out during the conceptual design phase. In this context, design refers to the generation of suitable product geometry and relevant attributes to satisfy the performance requirements. Within a modern design and optimization framework, iterative simulations are frequently practiced by the designers to generate an optimized geometric representation.

Considering a modern design and optimization framework-DEE, it not only illustrates the general design and optimization process but also includes the supporting KBE techniques. According to La Rocca [2], the DEE contains a geometry centric parametric model generator, so-called Multi-Model Generator (MMG), as well as disciplinary analysis modules. It starts with an initiator, which represents a product instance with initial input values. The core of the DEE is an MMG, which includes a product model generation module and one or more disciplinary view generation modules. The product model generation is realized by instantiating the master geometry composed by High Level Primitives (HLPs), while the disciplinary views generation is implemented by Capability Modules (CMs). HLPs are defined as basic design elements of a geometric

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