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Manufacturing System Design Decomposition: An Ontology for Data Analytics and System Design Evaluation

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Abstract

This paper builds on prior research to develop the Manufacturing System Design Decomposition (MSDD) from the perspective that it may serve as an ontology for evaluating the efficacy of manufacturing system design and implementation. Common ontology processes and formats were compared and contrasted to Axiomatic Design. The MSDD concept was translated into Web Ontology Language (OWL) and an XML format for comparison. An application in Automotive manufacturing system design was discussed from the Architecture Viewpoint of Ontology.

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Nomenclature

AD	Axiomatic Design
CN	Customer Need
FR	Functional Requirement
DP	Design Parameter
MSDD	Manufacturing System Design Decomposition
OWL	Web Ontology Language
RDF	Resource Description Framework
XML	eXtensible Markup Language

1. Introduction

A common question asked in all manufacturing process design is “how good is this design?” Designers always want to put the context of the design being considered against a heuristic to optimize and improve their design. Conversely, a heuristic can be used by the designer to determine when it is sufficient to be released. Cochran et al. [1] present an application of the Manufacturing System Design [2] Decomposition (MSDD) and a simple quality heuristic to evaluate the quality of a manufacturing system. In this paper, we will further explore this application of Axiomatic Design [3–5] from the Architecture

Viewpoint of ontology as a means for evaluating the efficacy of manufacturing system design and implementation [6, page 5]. To further strengthen this concept, we show a translation of the MSDD into standard ontology formats and compare it to a simple XML data interchange format. Applications in Automotive manufacturing system design are discussed from the Architecture Viewpoints of a computer science ontology and custom designed XML schema with respect to the Manufacturing System Design Decomposition developed with Axiomatic Design.

1.1. Axiomatic Design

Axiomatic Design was created to turn design from an “art into a science” [3]. The design axioms provide a means to quantify whether a design is effective or not. For instance, Dr. Nam Suh developed the Axiomatic Design approach in order to find a means to quantify common elements between good design and to contrast them with poor design. His investigation led to focusing on the relationships between customer needs, Functional Requirements (FRs) and the means of achievement of functional requirements through Design Parameters (DPs), encapsulated in two Axioms. The goal of any design, Suh said, is to reach the highest quality design solution that satisfies customer needs while minimizing resources used as quantified in Equation 1 [7,8].

$$\text{quality} = \frac{\text{Satisfaction of Needs}}{\text{Resources consumed}} \quad (1)$$

The result of Axiomatic Design is a structured description of systematic satisfaction of customer needs¹ through the development of comprehensive requirements in the fewest iterations [9].

In Suh's own words, "Axiomatic Design defines design as the mapping process from the functional domain to the physical domain, with the aim of satisfying the functional requirements specified by the designer" [3, page 26]. Once a proper set of need-driven requirements are generated, designers search for appropriate Design Parameters (DPs) that are able to meet the FRs. Each FR and DP are considered for first-order effects and are linked together by the design matrix given by $\{\mathbf{FR}\} = [\mathbf{A}]\{\mathbf{DP}\}$. AD's first axiom specifies that coupling among FRs is caused by the selection of DPs. If the design matrix only has non-zero elements on the diagonal, it is "uncoupled" and easily optimized. In addition, since the design is uncoupled, elements can be changed due to changing needs or availability of resources. If the design matrix is triangular, it is "decoupled" and can be solved if the DPs are set in the right order i.e. "path-dependent." Any other configuration of non-zero elements results in a "coupled," design which makes optimization very difficult. Changing one element affects many others, requiring that all elements must be taken into account during the design process.

AD's second axiom then suggests that the best solutions are the ones with "minimal information" in the information theory context. Simply put, systems that have an operating range within the design specification range have the highest probability of success and, by definition, have the minimum information content [3].

Axiomatic Design (AD) is a methodology for matching customer needs (or attributes) to the functional requirements then design parameters for an instance of a solution [3,4]. Traditionally this approach has been applied directly to manufacturing or product design problems such as designing a rocket parachute release system [10], or manufacturing system [11]. However, this methodology is general enough that it can be employed in any system that needs to fulfill a set of "needs."

Needs may include ROI of financial systems [12], airport special-needs assistance [13], and even getting people to pay their taxes [14]. Foley et al. have explored using Suh's consideration of complexity with AD [5] for puzzles, physical security, unique identification, and sabotage [15].

1.2. Manufacturing System Design Decomposition

The Manufacturing System Design Decomposition (MSDD) was proposed by Cochran et al. [16] to support the design and improvement of manufacturing systems. The MSDD was developed using Axiomatic Design. Some successful MSDD applications have been reported in the literature [2,11,17–22].

The primary functional requirement of the MSDD is to maximize long-term return on investment (ROI) [16]. ROI has been criticized as a measure of manufacturing performance based on the claim that it does not encourage long-term improvement [23,24]. For a system to be sustainable, Kaplan argues that a system must focus on the means (the work) to achieve system objectives, called FRs by the MSDD. Johnson and Bröms [25]

argue that long-term ROI is an acceptable requirement of a manufacturing system [26]. The design parameter used by the MSDD to achieve FR1: Maximize long-term return on investment, is DP₁: Manufacturing system design. The FRs at the next level of decomposition in the MSDD are components of ROI (t_{roi}) as given by $t_{roi} = \frac{E_R - E_C}{E_{C_0}}$ where E_R is revenue/period, E_C is cost/period, and E_{C_0} is initial investment.

The solution of Manufacturing system design (DP₁) is then decomposed into three sub-requirements: FR₁₁ Maximize sales revenue, FR₁₂ Minimize manufacturing costs, and FR₁₃ Minimize investment over the system life cycle. DPs are selected to satisfy the stated FRs as guided by the Independence Axiom².

$$\begin{Bmatrix} \text{FR}_{11} \\ \text{FR}_{12} \\ \text{FR}_{13} \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{bmatrix} \begin{Bmatrix} \text{DP}_{11} \\ \text{DP}_{12} \\ \text{DP}_{13} \end{Bmatrix} \quad (2)$$

The MSDD is a partially coupled or (path-dependent) design. The path-dependent design of the MSDD illustrates that minimizing operating costs and investment at the expense of customer satisfaction are improper means to achieve the highest-level goals/FRs of the manufacturing system.

This path-dependent finding is consistent with other findings in the literature. Similar to the MSDD finding, Ferdows and Meyer [24] developed a "sand cone" model, indicating manufacturing systems should be built by first starting with quality, then dependability, then reaction speed and flexibility, and finally on cost efficiency. Also, Fillippini [27] presents empirical evidence of different aspects of manufacturing performance. He found that compatibility between on-time delivery and economic performance occurred only when consistency in output quality had been achieved.

In the case of manufacturing systems, a common trend regarding the design of systems has emerged as codified by the MSDD and use of Axiomatic Design in its development. For this reason, Axiomatic Design, and the MSDD as an instance of Axiomatic Design in design development should be investigated as an Ontology for design. Pintzos et al. [28] provide an overview of the use of ontologies in harmonizing Production Performance Indicators.

1.3. Ontologies

To evaluate the MSDD as a possible ontology, we must first understand what an ontology is. Busse et al. [29] present the various views on ontology definition as a simulated dialog between an information scientist, a philosopher, and a psychologist on the topic of ontologies. Ontologies are considered generally in one of two domains: philosophy and information science.

In philosophy, ontology is closer to the original definition "science of being" and focus on what it means to classify and categorize the interaction of being. The terminology was first introduced by Christian Wolf in the 18th century as part of a discussion of "how things exist" in a theoretical way. Greek

¹be it a system, an artifact, or a process

²See [16] for the full decomposition.

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