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Engineering Analytics: Research into the Governance Structure Needed to Integrate the Dominant Design Methodologies

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ENGINEERING ANALYTICS: RESEARCH INTO THE GOVERNANCE STRUCTURE NEEDED TO INTEGRATE THE DOMINANT DESIGN METHODOLOGIES

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Abstract

In the ASEM-IAC 2014, Cotter (2014) explored the current state of engineering design, identified the dominate approaches to engineering design, discussed potential contributions from the new field of data analytics to engineering design, and proposed an Engineering Analytics framework that integrates the dominate engineering design approaches and data analytics within a human-intelligence/machine-intelligence (HI-MI) design architecture. This paper reports research applying ontological engineering to integrate the dominate engineering design methodologies into a systemic engineering design decision governance architecture.

Keywords

Engineering Analytics, HI-MI Design

Introduction

The ABET definition of engineering design (2013-2014) is "the process of devising a system, component, or process to meet desired needs." ABET engineering design elements include:

- An iterative decision-making process applying basic science, mathematics, and engineering knowledge.
- The optimal conversion of resources to meet stated needs.

ISO/IEC/IEEE 42010:2011, *Systems and software engineering — Architecture description* expands on the concept of engineering design by adding the requirement for a meta model description of an integrated hardware-software architecture through multiple views that capture all stakeholder concerns. Simon (1996, p. 9) generalized the engineering design outcome as the description of an artifact, its organization and functioning, and the interfaces between its inner and outer environments. Winograd and Flores (1986) noted that engineering design does not create artifacts that reflect only existing domains, but engineering design also creates new domains through its artifacts.

Cotter (2014) proposed updating these definitions to 21st century capabilities by integrating the dominant engineering design approaches and data analytics innovations within a human-intelligence/machine-intelligence (HI-MI) cognitive architecture. This paper updates research into establishing systemic design governance under which the dominant engineering design approaches can be integrated into a systemic HI-MI engineering design cognitive architecture. The paper will review the dominant design methodologies with a focus on defining the overlaps among and gaps between these methodologies. The paper will then summarize the ontological engineering methodology using frames and first-order logic being applied to build the formal axioms, classes, functions, and relations of fundamental HI-MI design decision governance on which integration will be based. Finally, the paper will discuss future research required to verify and validate the design governance architecture and the implications for the new Engineering Analytics domain.

Dominant Engineering Design Methodologies

For this research, the criteria for defining dominant engineering design methodologies was that a given methodology be based on a set or system of methods, axioms, principles, and rules. Given this criteria, traditional engineering design processes were eliminated as methodologies, because they are a general series of steps that engineers use in creating products and processes. Such general step-based processes include: (1) the waterfall model, (2) the spiral model, (3) the V-model, (4) the top-down model, (5) the bottom-up model, (6) the middle-out model, (7) model-based design, (8) production-deduction-induction, (9) agile design, (10) adaptive product design, (11) integrated product development, and (12) the total product life-cycle model. Each of the traditional design processes present a different view of the design process steps but lack necessary and sufficient principles or axioms on which to build systemic design governance.

Concurrent Engineering Design

Concurrent engineering design was admitted as a dominant engineering design methodology, because it is built on four complex systems design principles (Yassine and Barha 2003).

> ***Iteration principle***: The design process iteratively decomposes and re-decomposes systemic functional requirements into performance dimensions versus operating and environmental constraints and tests to determine the level of performance attainment versus constraint satisfaction.
>
> ***Parallelism principle***: From Amdahl's law (1967), complex systems must be highly parallelizable in order to be scalable. Amdahl's law notes that any parallel system's performance will be limited by a small number of sequential operations that cannot be parallelized. The design of complex systems requires a corresponding parallelizable design process in which evolving design information is shared efficiently among the conceptual, embodiment, and detail design phases.
>
> ***Decomposition principle***: The parallelism principle necessitates that complex systems be decomposed as much as possible into independent subsystems whose collective functionality yield the desired behavioral performance of the system itself. The degree of achievable independence is governed by the level of feedback interaction among subsystems.
>
> ***Stability principle***: Complex systems must exhibit multiple states of designed equilibrium performance that are robust against variations of internal subsystems functionality and external environmental chaotic reactions. The stability principle requires viable systemic behavior with sufficient feedback control among subsystems to achieve designed performance behavior.

Concurrent engineering builds design theory based on Hongo's (1985) scientific theory of design.

1. Design theories must be based on and derived from facts.
2. Laws of nature are absolute and unchangeable.
3. Designers can attain design goals through a given design process (i.e., no one design process is inherently dominant).
4. A design process is useful to accomplish design goals as long as it is applied consciously (i.e., the designer must understand the strengths and weaknesses of the design process applied).
5. Intuitive design should supersede the design process.

It is the application of facts and the laws of nature through intuitive design that leads to the discovery of new design theories. Being process independent, concurrent engineering may be applied within any of the above listed traditional engineering design processes.

TRIZ

The second design methodology admitted based on principles was TRIZ. Altshuller (1984) developed 40 principles of invention and the process of creative problem solving from the review of approximately 40,000 patents. The key to TRIZ creative problem solving is to define a contradiction which needs to be overcome in order to solve the problem by considering which of the 40 principles may be applied to achieve the solution. The search for a solution process is guided by the following heuristics.

> *Preliminary Analysis* to clarify the problem definition and solution constraints.
>
> The *Contradiction Matrix* lists technical contradictions between the attribute or characteristic to be improved and other unit attributes or characteristics that can be adversely affected by its solution.
>
> The *Separations Principles* needed to resolve the technical contradictions.
>
> The *Standard Approaches to Inventive Problems* lists typical classes of inventive problems and recommended solution approaches. These are presented in Su-Field Analysis.
>
> The symbolic modeling approach of *Substance-Field (Su-Field) Analysis* to document required transformations of the technical processes and systems needed to resolve the technical contradictions.
>
> The *Algorithm for Inventive Problem Solving* is selected from a set of logical sequential procedures for eliminating the contradictions.
>
> The *Agents Method* is a graphical, logical method of forward and backward bidirectional steps between the design problem and the desired solution to assure correct statements of the initial problem and the desired final solution.

Like concurrent engineering design, TRIZ is a design methodology that may be applied within any of the above listed traditional engineering design processes.

Axiomatic Design

Axiomatic Design is a systems design methodology that transforms customer needs into functional, physical, and process requirements using matrix methods. Functional requirements are related to design parameters through the matrix operations [FR] = [A][DP], where [A] is the design matrix and [DP] are design principles or axioms. The two axioms used in Axiomatic Design (AD) are:

> ***Axiom 1***: The Independence Axiom. Maintain the independence of the functional requirements (FRs). The Independence Axiom states that when there are two or more FRs, the design solution must be such that each of the FRs can be satisfied without affecting any of the other FRs.
>
> ***Axiom 2***: The Information Axiom. Minimize the information content of the design. The design effort may produce several designs, all of which may be acceptable in terms of the Independence Axiom. The Information Axiom provides a quantitative measure of the merits of a given design, and thus is useful in selecting the best among those designs that are acceptable. In addition, the Information Axiom provides the theoretical basis for design optimization and robust design. (Suh, 2001)

These Axioms are satisfied when the design matrix [A] is either diagonal or lower triangular, which yields an *uncoupled* design or a *decoupled* design respectively. These Axioms are not satisfied when the upper triangular element are greater than zero yielding a *coupled* design. In the coupled design, each FR will be affected by changes in the DPs of the other FRs, and the designer must make tradeoff compensations for the effects of changes in DPs on all FRs. Suh (2001) developed Axiomatic design theorems and corollaries to identify optimum designs for each type of coupling. Like concurrent engineering design and TRIZ, axiomatic design is a methodology that may be applied within any of the above listed traditional engineering design processes.

Design for Six Sigma DMADV

Design for Six Sigma (DFSS) differs from the design approaches discussed previously in that DFSS seeks to integrate the Six Sigma philosophy of achieving Six Sigma quality, 3.4 ppm nonconforming, with scientific design methods. DFSS works systematically from a high level of abstraction identifying and mapping customer expectations and requirements to a low level of abstraction through the use of mathematical models and empirical testing of variance reduction and design robustness. Whereas Axiomatic Design seeks to achieve uncoupled or decoupled designs, DFSS can work with coupled designs through the identification and mapping of sources of variability. DFSS was admitted as a dominant engineering design methodology, because it is built on the Six Sigma principles:

- Focus on customer expectations and requirements.
- Understand how work gets done and remove non-value added waste.
- Manage by facts and identify the root causes of problems (variations) through statistical analyses.
- Be pro-active in systematically eliminating variation and continually improving the process.
- Involve people in Six Sigma through cross-functional teams.
- Be thorough but be flexible with a focus on creating robust products, processes, and systems.

DMADV is the scientific basis for DFSS product, process, or systems design. The DMADV acronym stands for:

> **Define** design goals, objectives, and standards that align with the product, process, or system performance goals.
>
> **Measure** and identify characteristics of the product, process, or system that are Critical To Quality (CTQ), Cost (CTC), and Delivery (CTD) of performance.
>
> **Analyze** the data that encodes the design problem by building statistical models, and identify structural and random sources variance from product, process, or systems performance goals.
>
> **Design** changes that will ideally eliminate or minimally minimize the source of variation from performance goals.
>
> **Verify** that the selected design will meet the performance goals.

The Integration Problem

Independently, each of the dominant design methodologies set forth principles and axioms of design, with some notable overlaps and gaps, but differing processes for arriving at design solutions. Review of the literature reveals cases where Axiomatic Design has been applied within the context of Concurrent Engineering and Concurrent Engineering within the context of Axiomatic Design, and Axiomatic Design and TRIZ has been applied within the context of DFSS. There has been, however, no research toward systemically integrating these design methodologies within a design governance framework. The current gap in knowledge is in how to integrate the dominant engineering design approaches under a design governance framework such that they form a coherent and consist design domain that can be applied within a unified HI-MI cognitive design architecture. An HI-MI architecture is necessary to integrate the human creativity intelligence that is required for envisioning revolutionary breakthrough designs with machine intelligence that is required for efficient search, data and knowledge acquisition, and optimization of evolutionary incremental designs. One of the Engineering Analytics fundamental axioms is that it is only through the appropriate integration of human creative design intelligence and machine efficient design intelligence that the revolutionary→evolutionary→revolutionary→… design cycle can optimally or near optimally output new products, services, or systems that provide emergent systemic functional utility and strategic advantage within a mission context and minimized risk of latent failures. The axiom is self-evident because (1) humans have noted limited capacity for storing and processing vast quantities of data and knowledge but seemingly unlimited capacity for discovering or creating new knowledge required for revolutionary design solutions, whereas (2) computing machines have no or limited current capacity for discovering or creating new knowledge but massive capacity for capturing, storing, and processing existing data and knowledge required for the efficient assembly of evolutionary design solutions.

Ontological Engineering of Engineering Analytics Design Governance

Until now, ontologies and their corresponding problem solving reasoning methods (PSRMs) have been designed to address the general design process ontology or specific design knowledge domains. In order to integrate the dominant design methodologies within a design governance framework, this research must extend ontological-PSRM to a higher order, non-domain specific level. The resultant design governance framework, however, must also be designed to permit mapping into all possible domain specific design spaces.

Current research is focused on developing the conceptual design knowledge representation ontology frame. Whereas heavyweight ontologies typically start with definition of classes, this research starts with the definition of the universal design axioms that govern the subsequent definitions of design classes, functions, relations, and instances. The first five axioms specify the purpose of all design processes.

> ***Existence Axiom:*** Every designed product, service, or system exists to produce a set of outcomes useful to itself and entities dependent on it.
>
> ***Mission Axiom***: Designers must specify the minimal set of tasks mapped to associated outcomes that the product, service, or system is charged with accomplishing in order to produce specified useful mission outcomes under specified environmental conditions.
>
> ***Task Axiom***: Each designed task must be comprised of a minimal set of energy and information transformation functions and structural relations among those functions so as to achieve the task's specified outcome.
>
> ***Design Axiom***: Designers must apply a minimal set of design principles, models, and processes (the minimal set of energy and information transformation design functions and structural relations among those design functions) for conceiving and architecting the product, service, or system structure, energy, and information mappings to tasks necessary and sufficient for mission accomplishment.
>
> ***Usefulness Axiom***: The usefulness of mission outcomes can be experienced only by the entities who consume the product, service, or system's outcomes.
>
> ***Pareto Critical Axiom***: The entities that experience a product, service, or system's outcomes may or may not be able to define fully the task functions and relations that yield outcome usefulness; however, designers, through interactions with those entities, must determine the Pareto critical performance, cost, and delivery parameters of those functions and relations in order to achieve minimum mission usefulness in their designs.

From Concurrent Engineering, the first two axioms identify design bounds.

> ***Parallelism Axiom***: Complex systems must be highly parallelizable in order to be scalable.

> ***Decomposition Axiom***: The parallelism principle necessitates that complex systems be decomposed as much as possible into independent subsystems whose collective functionality yield the desired behavioral performance of the system itself.

From Axiomatic Design, the next two axioms define general design classes in terms of decomposition of critical functions and relations.

> ***Independence Axiom***: Maintain the independence of the functional requirements (FRs).
>
> ***Information Axiom***: Minimize the information content of the design.

Joint application of the Independence and Information axioms provide the basis for design process axioms.

> ***Design Information Axiom***: All design processes must begin with a necessary and sufficient set of definitions of the product, service, or system's mission and the set of Pareto critical functions and relations that map tasks to outcomes.
>
> ***Design Decoupling Axiom:*** The design process must work from serial coupled or decoupled functions and relations toward parallel uncoupled functions and relations by removing waste and reducing structural and stochastic sources of variation.
>
> ***Design Modeling Axiom:*** To the degree that series-parallel coupled and decoupled functions and relations remain in a design, the designer must build necessary and sufficient model representations of those functions and relations that map tasks to outcomes through the application of design principles or mathematical models.
>
> ***Design Iteration Axiom:*** The Design Decoupling Axiom and the Design Modeling Axiom can be accomplished only through design processes that iteratively decomposes and re-decomposes series-parallel coupled and decoupled task functions and relations into performance, cost, and delivery outcomes within specified environmental constraints.
>
> ***Design Sufficiency Axiom:*** The product, service, or system design representation is sufficient only when its predicted mission outcomes exhibit multiple states of designed equilibrium performance that are robust against variations of internal subsystems functional interactions and external environmental chaotic reactions.

Continuing Research into Engineering Analytics Design Governance

Given the above set of general engineering design axioms, current research focuses on applying frames and first-order logic to engineer ontological design classes, functions, and relations necessary and sufficient to integrate the dominant design methodologies within a systemic HI-MI design decision governance framework. This research is being carried out in three steps: (1) Identify each dominant design methodology's explicit ontology; (2) if a dominant design methodology does not state an explicit ontology, engineer its ontology from its principles, axioms, and methods; and (3) engineer the overarching design ontology required to integrate the dominant design methodologies ontologies. Programming of the unified HI-MI engineering design cognitive architecture will proceed partially in parallel with the engineering of the HI-MI design decision governance framework. Future research will then be initiated on axioms and ontologies necessary to specify general engineering mathematics, physical models, and simulation models for subsequent programming into the HI-MI design decision governance cognitive architecture. Future research beyond the general engineering models will be needed to develop engineering domain specific axioms and ontological classes, functions, and relations necessary for programming domain specific HI-MI design decision governance into the general HI-MI design cognitive architecture.

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