Applying Systems Modeling Approaches to Building Construction

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Abstract – Current building modeling environments lack the ability to support coordinated, incremental and systematic description of project requirements, design specifications, and the set of interactions that emerge among them, from different stakeholders, during building design. This paper discusses the prospect of a system-centric modeling framework that integrates a parametric CAD tool with a system modeling application to assess design intent based on construction-specific knowledge. The CAD tool provides strong geometric modeling capabilities, while system modeling allows the description of feature-based design specifications, aligned with construction standards and construction know-how. The ultimate goal of the proposed approach aims for the identification of conflicting interactions between design specifications, from different building material systems and stakeholders, to prevent design errors and on-site rework. The proposed framework will enable collaborative scenarios between Model Based System Engineering and BIM based on parametric, simultaneous, software integration to reduce human-to-data translation errors, improving model consistency among material systems, BIM tools, and project stakeholders.

Keywords –

Building Information Modeling; Model Based Systems Engineering; System Modeling Language; Building Construction; Knowledge-Based Design.

1 Introduction

In building construction, it is common that after the execution of a project, certain stakeholders will not be pleased with the manufacturing accuracy or overall quality of the final product [1]. These situations often occur in buildings due to the construction method was not precise enough, specifications were not properly communicated [3], or, as is often the case, due to the suggested tolerances were unachievable or unrealistic. In addition, design errors arise when design, as documented, reflects the designer's intent, but that intent is flawed due to a lack of information about system implications or due to wrong assumptions about material behavior and assemblies. All these factors produce significant geometric deviations that must be considered and mitigated as part of the construction requirements and specifications development stage.

Likewise, coordination issues among modeling environments, construction specifications, and knowledge are important sources of geometric variability [4]. These issues are evident when assembling multi-material systems, produced off site, by different vendors with different design workflows. In current practice, the individual material vendors apply their own tolerance specifications during shop-drawing production, based on their tacit knowledge of their own manufacturing and erection processes. Then, these individual models are not re-instantiated into an integrated CAD model to assess the effectiveness of the multi-material tolerance strategy. Therefore, disputes about tolerances incompatibility arise later during erection stages. Also, in any of these cases, as-built geometric deviations obtained in construction are usually much larger than commonly expected [5]. No matter what the reason is, these issues continue to spread in construction projects and contributes to cost and schedule growth due to design changes and errors [6] [7] [4].

Similarly, another common example of geometric variability occurs when designers make late changes to reduce construction costs associated with some building component (e.g. to replace welding in steel connections of a roof structure with bolted connections). While a modification may satisfy the specific construction requirement goal (e.g., reduce installation time), the systems-level implications and long-term side effects are usually not well understood (e.g. bolted connections may allow more movement at the joints, increasing deflection, leading to poor rain drainage, leakage, corrosion, and air infiltrations) and even if the problem is identified qualitatively, there exists no modeling framework in which to assess the implications of the problem quantitatively. Also, for the most common design-bid-build project delivery system, the team includes design professionals, a construction manager or general contractor, and many subcontractors [8]. In the early part of the project, the design team is primary – but in the later stages the general contractor assumes primacy. And so in this case, the responsibility for addressing specifications incompatibility issues is often not clearly defined. In managed contractual systems in which the construction manager does not self-perform the work, field personnel may not be familiar with the manufacturing specifications of the project, and they are also less likely to anticipate tolerance incompatibility problems [9]. In order to reduce these issues, BIM tools are required to represent a building at a whole-system level, capturing the functional and behavioral relationships that span across different domains, material systems, and lifecycle stages. It is in modeling these relationships that the identification of conflicts among design specifications can be facilitated. While early multidisciplinary integration and constant coordination efforts under a BIM-augmented workflow are certainly important means to reduce geometric variability problems [10] [11], they are not sufficient. Current tools and methodologies lack the ability to support coordinated, incremental, and systematic description of design specifications and the set of interactions that emerge across them during building lifecycle.

In contrast, during the past decades, aerospace engineering has largely improved its ability to managing geometric variability and manufacturing-specific knowledge [12]. The aerospace industry has taken advantage of modern computer-aided manufacturing technology to integrate CAD tools with manufacturing processes through a Systems Engineering (SE) approach. It is SE that allows linking together all the disparate elements of a product design into an intelligent product model, which can be continuously validated over its lifecycle. This is the key to enabling true model-based development [13]. Thus, the expansion of SE has facilitated the development of model-centric architectures, and the ability to integrate numerous domain-specific tools. This research advises how the tools promulgated by SE can generate new collaborative environments to facilitate the process of knowledge allocation in construction models. To achieve this goal, this research proposes a system-centric modeling framework that integrates a parametric CAD tool with a MBSE modeling platform. The CAD tool provides robust geometric modeling capabilities, while MBSE allows the modeling of building specifications from a system-level standpoint. Consequently, the identification of system interactions between construction specifications from different domain-specific tools and stakeholders is based on this CAD-MBSE integration.

The present research, which corresponds to number 2 of the following list, belongs to a wider area or investigation to develop an knowledge-integrated modeling framework for construction. Other parallel tracks of this study that will be part of complementary publications include:

1. Review of tolerances and geometric deviations in construction and engineering,
2. Study of the likelihood of using a MBSE approach to model and store reusable manufacturing knowledge and design specifications for construction,
3. Proposal of a model integration and model consistency approach among MBSE models, mathematical engines and BIM (CAD) models, and
4. Development and computational implementation of a system-level tolerances modeling and allocation based on a MBSE approach.

The expected general contribution of this research intends to establish a general MBSE approach for the representations of construction knowledge and tolerances interaction across building sub-systems and stakeholders. A further expected contribution, after the approach is fully developed, is to early identify conflicting design specifications to minimize costly late-discovered construction errors.

2 The Case of Construction Tolerances Issues

The main formal modeling element used to anticipate random (unintended) geometric deviations of manufacturing and construction processes is known as a tolerance. Tolerance has many different meanings based in the field that it applies. For this research, a tolerance is defined as the permissible limit or limits of variation in a physical dimension. Although the concept of tolerance is broadly understood, applicability of construction tolerances have not been adequately established due to the lack of knowledge integration during design stages, and the lack of multidisciplinary coordination among different stakeholders of project. Furthermore, many of the construction specifications cannot be assured from the beginning because they evolve during the course of a project. Early decisions about tolerances are usually made based on improper assumptions, or without an understanding of the "big picture" with respect to system implications. Decisions made late in a design stage are often taken without knowledge or consideration of earlier decisions, or without understanding of the effects that these changes will produce in other building systems. As a result, during project development, the state of knowledge about construction tolerances is diffuse, and no stakeholder has access to the entire knowledge base about what tolerances are realistic to prescribe. As it was discussed previously, there are a number of factors leading to a resulting building that differs geometrically from the nominal, dimensionally perfect, building model. The summary these issues is:

- Multiple material systems with different bodies of manufacturing knowledge [14];
- Geometry does not necessarily comply with manufacturability while being designed and later updates to remedy inconsistencies will increase the likelihood of mismatches with other components;
- Lack of knowledge representation and allocation methods for each material system [15] [14];
- Lack of integrated manufacturing knowledge traceability from specifications to geometry [16];
- Lack of manufacturing and tolerances verification methods [16]; and
- Lack of consistency across different tools and models [17].

The following section will discuss the main limitations of current BIM tools that produce some of the described shortcomings of system coordination and knowledge integration in building design.

3 Limitations of Current BIM

In current practices of architectural design, building engineering, and construction, products and systems are expected to perform at predicted levels. As Friedenthal et al. [18] states: "Competitive pressures demand that these systems leverage technological advances to provide continuously increasing capability at reduced costs and within shorter delivery cycles." In the building industry, this statement usually refers to a highly detailed set of requirements that challenge current methods of design, delivery, and operation of buildings. To successfully produce better buildings, the design and construction industry has to integrate computational tools that shift away from the traditional approach of independently-developed systems and stakeholders requirements. This is Building Information Modeling (BIM). BIM can be defined as a centralized modeling environment that allows connectivity of multiple vectors, including project information, assembly specifications, building operation, and building users [15]. However, the development of BIM, although crucial at the geometry level, has not been equally successful in developing well-defined transactional workflows to eliminate data interoperability issues [19].

Additionally, a building, as any other complex system, is not a static entity. Rather, it changes over time as sub-systems are incorporated or detached during the building lifecycle. These changes result in requirements and behaviors of constituent systems that may not have been anticipated when the system was designed [18]. Furthermore, in building design, multi-functional components are highly common. For example, a building roof covers the space of a building; protects the inner space from weather events; adds thermal protection to the interior; and enables the installation of other systems such as windows or solar panels. Any of these functions requires strict compliance with functional, structural, aesthetic, and economical constraints during building lifecycle. If no proper knowledge and project data integration platform is implemented, presumably, any change of the roof design, which is meant to improve some performance aspect, will result in the detriment or, at least, some change in some other functionality. As a proposed solution to this larger problem, the SE approach, has been extensively recognized in the aerospace and mechanical engineering industry to provide system solutions to technologically challenging and mission-critical problems that require knowledge management, analysis and model coordination [18] [20] [21]. The next section describes the Model Based Systems Engineering methodology and associated modeling language, compares document-centric and model-centric approaches, and gives an overview about how the figure of a systems architect can increase levels of interoperability and consistency among BIM tools and stakeholders.

4 Model Based Systems Engineering and the System Modeling Language

In the SE field, the development of a mature Model Based System Engineering (MBSE) approach allows the management of multiple domains and applications in a progressively complex Information Technology (IT) environment [22] [23] [24]. MBSE is defined as a practice of applying modeling and simulation for implementing the processes and practices of SE [20]. The main characteristic of a MBSE methodology is to link different modeling tools, from different domains, in a central model that allows interoperability and consistency between domains. Use of MBSE has led to the development of a general-purpose system-level architecture that allows multi-disciplinary modeling in different levels of abstraction. The modeling language for MBSE knowledge-modeling environment is the System Modeling Language (SysML), which was established by the Object Management Group (OMG) based on the Unified Modeling Language (UML). SysML is a general-purpose modeling language for systems engineering applications. It supports the specification, analysis, design, verification and validation of a broad range of systems and systems-of-systems [22]. By means of integrating SysML into the construction workflow tools, this research aims for the early identification of conflicting design specifications to minimize costly construction errors. This objective is proposed by programmatically linking a geometric BIM tool with a system engineering tool (based on SysML), and a mathematical simulation engine for analysis calculations. The proposed integration is intended to support the collaborative modeling of a building project as a “system-of-systems,” and to provide the computational infrastructure and knowledge necessary to fix conflicts when they are detected.

4.1 Document-Centric Approach for Managing Project Data

One of the important contributions of MBSE has been the development of model-based architectures that have enhanced the ability to share and exchange project data. This contribution, although significant, requires improved knowledge and skills of users to facilitate the adoption of model-based practices. However, even with the development of BIM and system engineering, the current practice of architectural design and construction still relies on the conventional document-centric approach (Figure 1) to deliver and manage building lifecycle data. This method usually emphasizes the generation of individual design documents, in hard copies or electronic file formats with restrictive interoperable capabilities, which are exchanged among the project stakeholders.

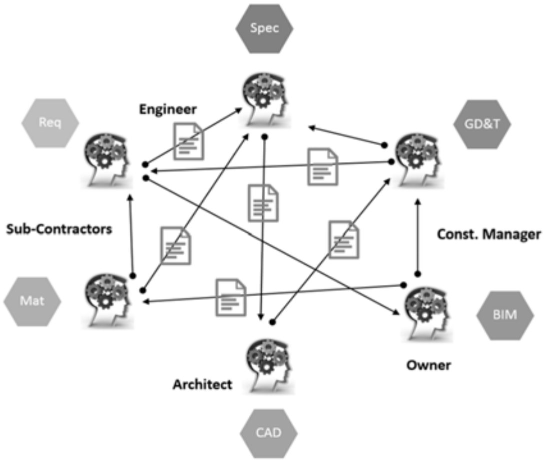

Figure 1, Document-Centric Architecture

Considering this increasingly complex and fragmented IT environment, the document-centric approach requires a significant amount of time to ensure that documentation is valid, complete and consistent. In the classic document-centric approach specifications are depicted in specifications trees. Then, a systems engineering management plan (SEMP) defines how the systems procedure fits in the project, and how all the concurring disciplines come together to develop the documentation necessary to satisfy the requirements in the specification tree [18]. Usually, these kind of relationships will be depicted in design documentation such as flow diagrams. However, flow diagrams of a document-centric approach lack interoperable functionality. Consequently, though a document-centric approach may be quite rigorous, it has a critical limitation when assessing the consistency and completeness of project data. For this approach to be successful, the software architecture of BIM must be transversal to different building stakeholders and tools, and the actor in charge of the document mapping must be consistent and constant in order to maintain a complete model. As [18] points out, The comprehensiveness, consistency, and relationships between requirements, design, analysis, and test data are hard to evaluate due to the fact that information is distributed across several documents. Understanding a particular view of the system and executing the necessary traceability and design-change impact assessments is clearly challenging. Applying this scenario to the AEC domain may lead to a deficient coordination of design requirements, which could subsequently lead to poor knowledge integration regarding material systems and manufacturing processes, and finally to quality issues when the final product is delivered.

4.2 Model-Centric Approach for Managing Project Data

As it has been described above, the document-centric approach for systems engineering –although having many advantages, suffers from an important disadvantage: model inconsistencies. This situation was one of the main motivations to propose this BIM-MBSE approach. With the MBSE approach, many of the intermediate deliverables of the modeling activities seen in the document-centric method can be generated automatically.

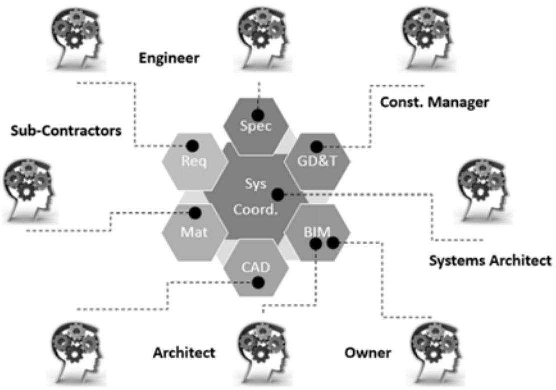

Figure 2, Model-Centric Architecture

As [20] explains, in the model-centric approach, the main product of those activities is an integrated, coherent, and consistent system model, produced through a dedicated systems modeling tool: the System Modeling Language (SysML). All other artifacts are secondary—automatically generated from the system model using the same modeling tool.

One of the important characteristics of a comprehensive BIM model is that it enables stakeholders to take informed decisions. Decisions made within a MBSE framework take place within a central repository, where each design decision is captured by a model element or a relationship among model elements. With the model-centric method, all objects depicted in different BIM or engineering tools are simply views of the underlying system model, they are not the model itself. And that difference is the core of the return on investment (ROI) that MBSE offers over the document-centric approach [20]. In a united MBSE-BIM model, as all modeling elements are programmatically and systemically integrated, any change that is produced will be automatically propagated to the rest of the model. It does not matter if the elements are depicted in a diagram that is user-defined or automatically created, or if the model is too large or complex. After all, the elements of the system models are just views of the real model, which keeps its internal consistency based on the seamlessly integrated nature of its modeling approach.

4.3 The Role of the Systems Architect

Similar to the functions of a BIM manager, an SysML-BIM framework requires an actor that assumes all the responsibilities for the creation of tool-specific integration routines, and proper knowledge allocation during coordination of trades and stakeholders. Also, besides modeling integration, another important function of the systems architect is knowledge integration. This task involves the creation and maintenance of design specifications and standards based on data collected from the different stakeholders. After all domain-specific models have been imported/linked, the systems architect will guarantee that knowledge-based verifications are executed right on time to meet project schedule or to discuss corrective actions with the trade-specific design teams.

In the AEC world, the skill of modelers has been challenged by the implementation of BIM, which is inherently 3D and requires a higher level of modeling skill. Most BIM authoring tools require that modelers assert the relationships between building objects as part of building BIM models, which is an additional challenge, but which makes the building model richer and more useful. The system model includes everything in BIM and adds sub-models for requirements and processes. Thus the modeling complexity is increased even further, leading to the identification of the “systems architect” as a managing entity. The next section presents the proposed general approach for building design, and describes its main functionalities to be developed in a computational implementation.

5 Proposed Design Methodology

In Figure 3, the depicted diagram represents the current approach to inform design in building construction. In this case, domain-specific knowledge is never formally integrated with the assembly geometry. Assumptions about material interactions and components design, rather than formal model-based assessments, create room for inconsistencies between design specifications and design geometry. In this research, a formal link between domain-specific knowledge and geometry is the proposed way to assure the full validation of building requirements and specifications. To implement this approach, the interactions diagram needs to incorporate a new element that will open several other kinds of relations in the process: a geometric constraint.

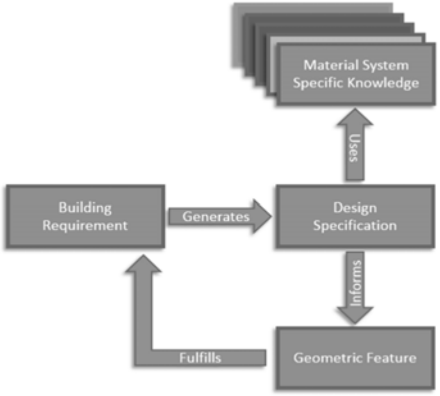

Figure 3, Modeling approach without the proposed framework

A geometric constraint is proposed as the negotiating point between domain-specific construction knowledge and design geometry (Figure 4). Furthermore, a geometric constraint can be the formalization of a piece of manufacturing knowledge. For example, a basic formula to calculate the minimum bending radius of sheet metal is r = t, where r is the radius of the bending and t is the thickness of the part. Then, the mathematical expression r = t represents a portion of domain-specific manufacturing knowledge. This basic piece of knowledge can be automatically evaluated in a geometric feature, if CAD parameters and knowledge are linked together. In order to make this geometric constraint operational, most of the exchanges depicted in Figure 4 must be programmatically formalized. For this research, the material system-specific knowledge will be formalized as a specialization of SysML requirements, which will be programmatically linked to their mathematical formalizations as design constraints. Also, another part of the process, which involves data exchange among specifications, geometric constraints, and geometric features, must be automated. As it can be seen in Figure 4, design specifications will inform geometric features, and parameters of geometric features will populate the domain-specific constraint, which will verify that the design specification is in compliance.

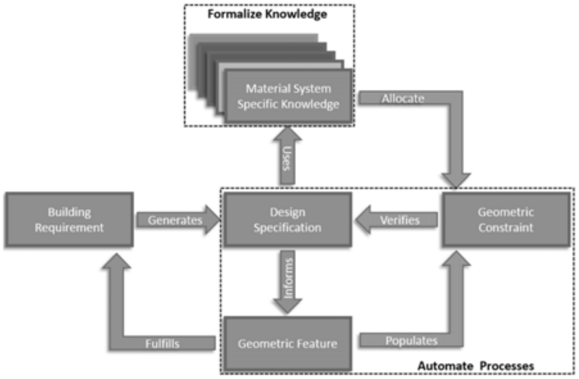

Figure 4, Modeling Approach as proposed

5.1 Functionalities of the proposed modeling framework

In order to implement the proposed modeling framework, the following list of general functionalities is required:

- Model-to-Model Transformation: structural, feature-based decomposition of parametric CAD models into system models.
- Model Integration Approach: parametric, seamless software integration for knowledge allocation, analysis, and verification to reduce human data translation.
- One Truth, multiple model views: centralized project requirements, geometry, and design specifications in an interoperable modeling environment.
- Machine Readable/ Executable: CAD geometry programmatically integrated to manufacturing know-how through knowledge-based mathematical and logical constraints.
- Model Consistency Approach: On-demand model-to-model and tool-to-tool consistency assessment and model data update.

The next sections will convert the previous set of system requirements into specific activities that will be programmatically implemented after full development of this research.

5.2 Required Activities to Implement the Proposed Framework

The methodology to full develop the proposed modeling framework is composed of the following six activities, which will be entirely implemented during future stage of this project:

1. Structural Decomposition: Includes the creation of a feature-based representation of the CAD model in the SysML environment. It follows the project>assembly>part>feature>parameter approach to describe geometry. Also, it creates a data graph based on CAD meta-model.
2. Knowledge Acquisition: Corresponds to the domain-specific knowledge, and its formalization, necessary for specifications compliance analysis or optimization/verification processes of an assembly or section of a building. This process will be carried away by adding specific rules as requirements in the SysML environment. All knowledge created will be stored within a domain-specific knowledge repository in the SysML model. This repository will have requirements that lead to design specifications represented as mathematical expressions.
3. Knowledge Allocation: CAD features decomposed in numeric parameters from CAD data will be linked to mathematical constraints that carry domain-specific knowledge. The allocation process will be executed automatically so that manual data translation is avoided. Then, the application will query the features and material types of the imported CAD, and will offer options to link specific pieces of knowledge that match those details.
4. Parametric Execution: The application will evaluate all the domain-specific knowledge constraints, through a mathematical engine, by using instances data obtained from the CAD models. The results of each parametric evaluation will be stored so that the user can compare them and pick the best analysis scenario for a given analysis context.
5. Specifications Verification: Routines coded for this implementation in SysML will evaluate and verify the consistency between CAD metrics and the formal description of design specifications defined for the specific building project.
6. Knowledge-Compliant Geometry Update: This stage defines a series of functions that will consolidate changes produced in the model on either the CAD or the SysML side. In an integrated framework, changes might be produced in different domain-specific applications. For this framework, if changes that were positively evaluated by the application were produced on the CAD side, there will be an “update SysML model from CAD” command added in the SysML modeling interface. Conversely, if changes were made in the SysML side, there will be an “update CAD model from SysML” command.

At a general level, the main practical functionalities of the proposed application are:

- Adding knowledge-compliant, feature-oriented, case-based design specification to the CAD model;
- Automatically assessing specifications of parts and assemblies to identify possible system conflicts;
- Upgrading “nominal geometry” by adding feature-oriented considerations based on material-system-specific engineering and manufacturing knowledge; and
- Evaluating and validating tolerances and clearances specified for parts and assemblies.

6 Conclusions

This research proposes a system-based, knowledge-aided modeling framework that integrates a parametric CAD tool with a system modeling platform to assess specifications compliance in building construction. Main motivations of this approach are the lack of manufacturing-specific knowledge available for designers in design stages, the lack of manufacturing compliance and verification methods for BIM models, and the lack of multidisciplinary consistency among BIM tools. This research argues that the aforementioned problems can best be addressed in the context of an integrated knowledge-modeling platform. With proper development, the framework proposed by this research could create a new kind of building design paradigm: A modeling environment that virtually and simultaneously brings to the table all domain experts, anytime that building feature is created.

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