Enhancing Trustworthiness and Formalization in the Construction Industry with Modeling Languages and Ontologies

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Abstract
The construction industry is rapidly evolving with the advent of new technologies. Despite this progress, large-scale projects remain plagued by complexity and diverse operations that hinder automation and productivity, leading to inefficiencies and lower profitability. These challenges are further amplified by traditional practices and the insufficient adoption of modern technologies. This research focuses on the adoption of Model-based System Engineering (MBSE), particularly on enriching System Modeling Language (SysML) models with ontologies. By leveraging ontologies as a comprehensive knowledge base that encapsulates essential details about the construction industry domain, providing formal support and enabling automated reasoning to verify model consistency. The proposed methodology aims at providing significant improvements in system design robustness and operational reliability, offering an effective solution for the automation and efficiency challenges in the industries. The introduction of the new SysML v2 standard promises to further enhance the integration between SysML models and ontologies, laying the groundwork for adapting the proposed methodology within the construction sector. Future research will explore the application of the methodology in the cement-based production industry, the modeling of legal contracts in SysML, and the integration of SysML models with blockchain technology to automate smart contract generation and enhance traceability in industrial operations.

Keywords
Model-based Systems Engineering, Ontologies, Knowledge Representation

1. Introduction

The construction industry is undergoing a significant transformation driven by technological advancements and the principles of Industry 4.0 [1], [2]. Despite the evolution of the construction industry, the inherent complexity and diverse operations of large-scale construction projects continue to pose substantial challenges in terms of automation and productivity enhancement. These challenges result in suboptimal profitability and operational inefficiencies. These issues are rooted in the industry's traditional practices and the underutilization of modern technological innovations, creating a substantial gap in the potential for innovation and improvement [3].

This study is part of a Ph.D. program co-funded by Build Trust[1], a startup, that seeks to address these challenges by introducing innovative approaches to the construction industry. By leveraging virtual modeling for planning and execution, along with a permissioned blockchain for transparent data sharing. The proposed approach aims to make information across the entire value chain available on a secure and immutable platform. Build Trust focuses on several key areas to enhance efficiency and transparency in large-scale construction projects by introducing Industrial Internet of Things (IIoT) sensors for monitoring the production of concrete, real-time tracking of on-site activities exploiting Building Information Modeling (BIM) models, transforming legal contracts into smart contracts for financial transparency, integrating on-site sensors for worker safety, and comprehensively tracking

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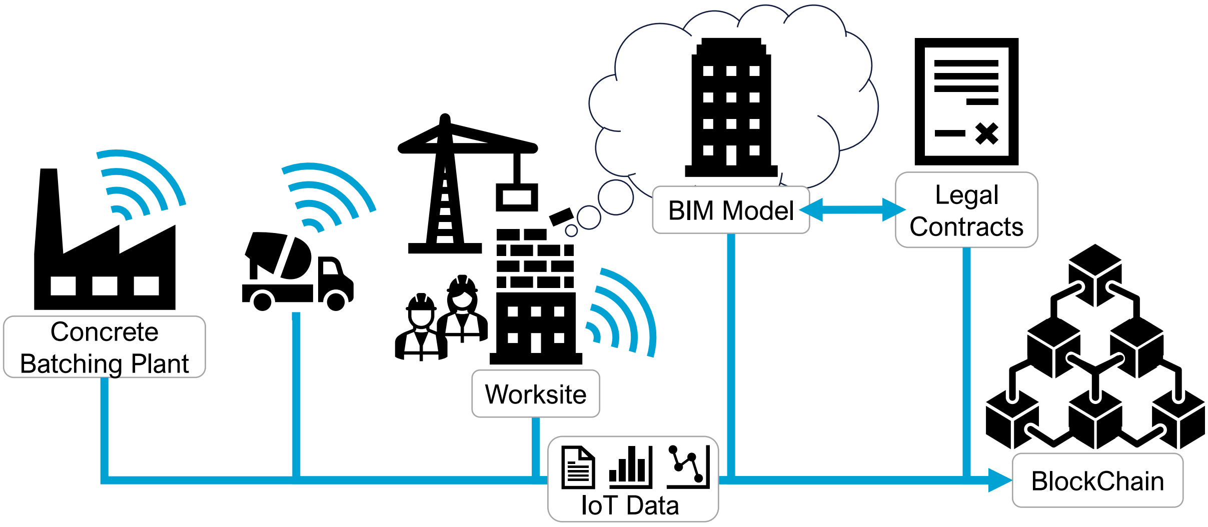

Figure 1: Overview of the integrated digital workflow in the construction industry. On the left, a Batching Plant equipped with IoT sensors collects production data. The concrete is then transported to the worksite, both of which are monitored by sensors that track the progress of the construction. The BIM model combined with legal contracts serves as the reference design model. On the far right, the blockchain securely tracks all collected data.

material usage to support sustainability goals. Figure 1 provides an overview of the core components and workflow in the Buil Trust vision.

To complement these technological advancements in the construction industry, the application of MBSE offers a powerful methodology to support all design phases by utilizing comprehensive models of the system being engineered [4]. MBSE aids in enhancing understanding, communication, and documentation of system requirements and design, thereby improving overall system reliability and efficiency. A key element in MBSE is the use of modeling languages, with SysML [5] being the de facto standard for modeling complex systems according to MBSE principles.

This research work contributes to the development of some Build Trust methodology's cornerstone aspects. In particular, it focuses on defining the modeling strategy to create comprehensive models written in SysML and enhancing them with the integration of formal descriptions and methods such as ontologies and semantic reasoners. Ontologies provide a formal, explicit representation of shared knowledge within a domain based on logical constructs. Ontologies allow the definition of concepts, relationships, and constraints, ensuring precise and unambiguous models. Ontology-based logical reasoning is enabled by semantic reasoner allowing the verification of model consistency. This research work aims to explore and establish how the modeling phase of SysML could benefit from the integration of ontologies and semantic reasoners.

As depicted in Figure 2, within the proposed approach, the system under analysis is initially modeled in SysML. The resultant model is then paired with a *Domain Specific Ontology*, which encapsulates all the relevant knowledge within that domain. The *Domain Specific Ontology* is based on community-maintained Information Resources (IRs), which include industry standards such as ISO or IEEE standards, alongside scientific publications and project reports.

Four distinct domains are considered for the Build Trust project: the plant for batching concrete, the production recipes for concrete, the construction sites, and the legal contracts involved in the construction process.

We are developing a toolchain able to parse SysML models and encode them into ontologies, which are described using the Web Ontology Language (OWL). The parser takes as input a SysML model and the corresponding *Domain Specific Ontology*; then, it generates a new ontology that combines the information from both sources. The newly generated ontology is then used to verify the consistency of the model. A semantic reasoner verifies the ontology consistency by checking logical inconsistencies. The reasoner provides feedback about the results of the consistency checks.

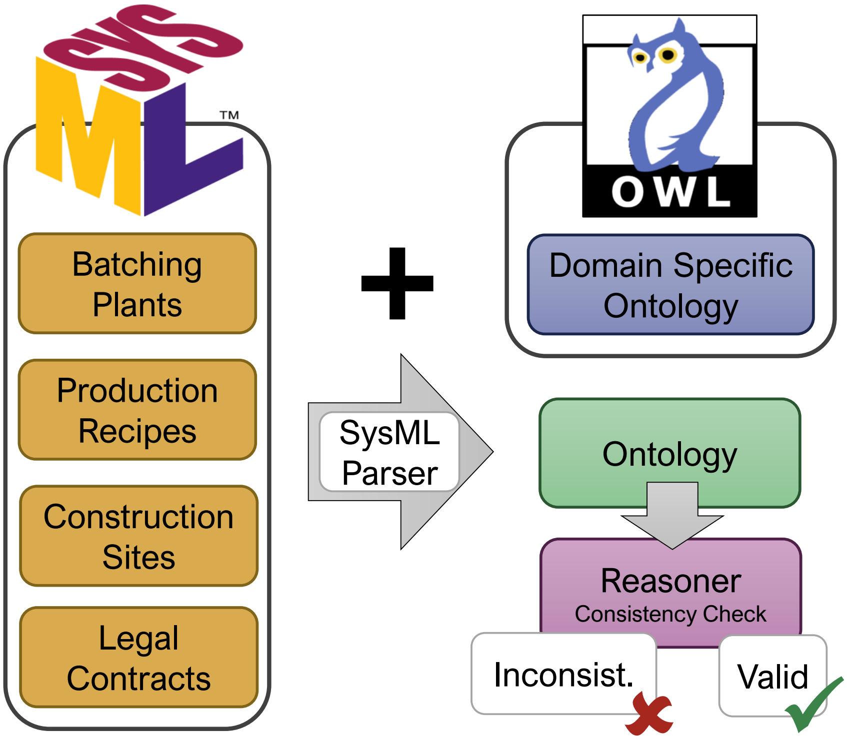

Figure 2: Overview of the proposed methodology. On the left, SysML models are paired with a *Domain Specific Ontology* tailored to the construction industry domain. This combination is used to create a new ontology based on the SysML models. The correctness of the model is then verified by checking its consistency.

The proposed methodology has been validated through its application to a fully operational manufacturing line within a research facility, showing its applicability in real-world scenarios.

2. Preliminary Results

Our preliminary work focuses on creating a first methodology combining SysML v1 with ontology reasoning. The work aims to enhance the modeling and verification processes of manufacturing systems within the context of Industry 4.0. The approach we presented in [6] involves creating a *Production Plant Ontology* that integrates the information contained in the SysML models with a *Foundational Ontology* acting as the *Domain Specific Ontology*. The *Foundational Ontology*, based on industrial standards, e.g., DIN 8580, contains all the necessary knowledge to describe production plants, including concepts such as physical machines, manufacturing operations, and their relationships. By mapping the SysML models onto the classes and relationships defined by the *Foundational Ontology*, we facilitate a formal representation of manufacturing knowledge. The resultant formalization enables automated reasoning to verify the consistency and correctness of the models.

The methodology relies on SysML to provide a structured representation of the production system and its machinery using Block Definition Diagrams (BDDs) according to the modeling approach described in [7]. Additionally, SysML Activity Diagrams are employed to model manufacturing operations and material transformations. Each manufacturing action performed by machines is represented by an Activity Diagram, which details the step-by-step process of transforming input materials into output products. Activity Diagrams capture the sequence of operations, the flow of materials, and the interactions between different components of the system.

Consistency verification is a critical component of the methodology. An automated reasoner, i.e., Pellet [8], is used to verify the consistency of the *Production Plant Ontology*. The verification process ensures that the models are not only consistent but also that the production recipes being modeled are coherent and executable within the specified production environment. The automatic generation of the ontology from SysML models is facilitated by a parser, which converts the SysML representations into OWL ontologies. The automatic conversion ensures that the models adhere to the formal structure required for automated reasoning.

2.1. Case Study and Results

The methodology in [6] has been validated in the Industrial Computer Engineering (ICE) Laboratory[2]: a research facility equipped with a fully-fledged reconfigurable manufacturing line. Specifically, a production recipe for engraving a plastic piece with a milling machine was modeled using SysML and subsequently encoded into an ontology. The consistency of the generated ontology was then verified using the reasoner, which ensured the correctness of the SysML model and the feasibility of the production recipe.

The SysML model being used in our case study comprised various elements essential for detailing the manufacturing machinery and processes, including 12 BDD, 48 activity elements, 28 relationships, and 36 Fork/Join elements. The *Foundational Ontology*, was used to encapsulate a substantial amount of information, resulting in an OWL file containing 972 XML tags, defining 312 axioms, 57 classes, and 19 types of properties. After applying our automated generation process to the SysML model, we noticed a substantial increase in the size of the resulting *Production Plant Ontology*. Resulting in an OWL file containing 1539 XML tags, defining 462 axioms. The ontology generation took 284 ms, and the consistency verification times were 1229 ms for a consistent ontology and 1660 ms for an inconsistent one.

Integrating SysML with ontologies offers several benefits. Firstly, it provides formal support to SysML models, ensuring precise and unambiguous representations of manufacturing systems. Thus, enhancing formalization enhances the reliability of the models by enabling automated verification processes that reduce manual effort and the likelihood of errors. Additionally, combining SysML with ontologies enriches the models with rigorous semantics, improving the overall reliability of the system design process.

3. Future Work

Several key advancements are planned to further refine and expand the presented methodology. While the transition to SysML v2 will offer new opportunities to enhance the approach, the primary focus will be on exploring the applicability of this methodology in other contexts, such as modeling legal contracts. Additionally, research will investigate the automatic generation of smart contracts directly from SysML models, with the aim of improving traceability and automation in industrial processes.

Following the Object Management Group's (OMG) 2017 request for proposal (RFP) for SysML v2, the SysML v2 Submission Team (SST) developed an upgraded version of the Systems Modeling Language. Approved by OMG, SysML v2 is now in the final stages of standardization. The most recent release specification can be accessed online [3]. SysML v2 aims at advancing the current SysML standard by improving the precision and expressiveness of the language, the consistency and integration among language concepts, tool interoperability, and usability [9].

SysML v2 lays its foundations on a new metamodel: the Kernel Modeling Language (KerML). SysML v2 is designed specifically for systems modeling, and is grounded in core declarative semantics based on formal logic. Unlike its predecessor, it is not constrained by Unified Modeling Language (UML), though it retains most of UML's capabilities. SysML v2 introduces enhanced visualizations with both graphical and textual notations, along a new concept called *metadata definition*, that replaces stereotypes and profiles from SysML v1, offering a more flexible and extensible way to customize the language. Such a feature is particularly useful for extending the language to support domain-specific applications.

[2]The ICE laboratory: https://www.icelab.di.univr.it/
[3]SysML v2 language specification: https://www.omg.org/spec/SysML/2.0/Beta2

The advent of SysML v2 and its new features could significantly enhance the integration between ontologies and SysML models. One of the most impactful advancements is the introduction of standardized Application Programming Interface (API), which marks a major improvement over the reliance on XML Metadata Interchange (XMI) for model interchange in SysML v1. XMI has historically posed challenges for tool vendors and users, especially when managing large and distributed models, due to its complexity in parsing, extracting, and processing data.

The standardized API introduced by SysML v2 facilitates the dynamic exchange of model data, improving interoperability across tools and applications. Such an improvement directly benefits the methodology presented in Section 2, where the integration of ontologies with SysML models could now bypass the complexities associated with XMI. By utilizing the new API, the process of generating ontologies from SysML v2 models becomes more efficient and streamlined: such an objective will be achieved via a thorough engineering work to make ontology generation faster.

SysML v2 replaces the use of stereotypes with the more sophisticated *metadata definitions*. Thus, it provides a more flexible and extensible mechanism to customize the language and tackle domain-specific requirements. In the context of integrating SysML models with ontologies, exploring how *metadata definitions* can be leveraged to improve the integration is a promising direction. Still, the potential for *metadata definitions* to enhance the precision and relevance of ontologies in representing domain-specific knowledge within SysML models requires further investigation.

Moreover, the methodology described in Section 2 is planned to be applied within the industry for the production of concrete. Such application will allow for the verification of the consistency and correctness of construction processes, showing that the methodologies developed are robust and applicable in different scenarios.

Additionally, we intend to leverage the knowledge gained from our preliminary research to model legal contracts in SysML. By applying the proposed methodology, we aim to simplify and improve the verification of consistency and soundness of modeled legal contracts. In the construction industry, legal contracts are typically written in natural language, making them extremely detailed and often difficult to comprehend, especially in large-scale projects. These contracts contain a wide range of critical information to ensure that all parties involved are clear on their rights, obligations, and the terms of the project. To obtain a comprehensive view of the construction industry, it is essential to model the information contained in these legal contracts.

Another area for future research is the relationship between blockchain technology and SysML, particularly in exploring ways to automatically generate smart contracts from SysML models representing industrial plants, with a focus on the information and data exposed by each machine. Automatically generating smart contracts would enable the publication of all relevant data on the blockchain, allowing the entire production chain to be tracked through data collected from IoT sensors. This integration ensures transparency, security, and efficiency across the process, significantly enhancing the traceability and reliability of industrial operations, and providing a solid foundation for managing complex industrial ecosystems. In addition, another critical aspect of this integration would be the automatic extraction of contractual constraints imposed by legal agreements. By encoding these constraints into smart contracts, the system could automate the monitoring and verification of contract compliance. Any violation of these contractual terms could be detected in real-time, triggering alerts or corrective actions. Reducing the potential for disputes and ensuring that all parties adhere to agreed-upon terms.

4. Concluding Remarks

In this work, we explored the integration of SysML models with domain-specific ontologies. The approach facilitates precise knowledge representation and automated reasoning, ensuring model consistency and improving system reliability. Looking forward, the forthcoming transition to SysML v2, with its enhanced capabilities such as a standardized API and more flexible language extension, will enable us to further refine and extend the proposed methodology. This will facilitate more seamless integration between SysML models and ontologies, making the approach even more effective and scalable across different industrial domains. Future research will focus on expanding the application of this methodology to other areas, including the modeling of legal contracts and the automatic generation of smart contracts from SysML models. These efforts are aimed at further enhancing transparency, traceability, and operational efficiency in the construction industry, ultimately contributing to its transformation into a more innovative and sustainable sector.

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