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A FEDERATED SIMULATION-BASED FRAMEWORK FOR ENHANCED CONSTRUCTION PROJECT PLANNING AND CONTROL

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ABSTRACT

This study addresses the need for integrated planning and control in construction projects by proposing a novel federated simulation framework. Despite the proven effectiveness of simulation in project planning and control, its adoption is hindered by complexity and limited reusability. High-Level Architecture (HLA) standards were explored to mitigate these challenges, yet they also pose complexities of their own. The proposed framework integrates simulation and HLA advantages within a single environment, offering a standard object model for mapping data, a decomposable simulation component that supports plug-and-play flexibility, and a data acquisition and integration component that supports real-time dynamic updates and scenario analysis. A prototype federation demonstrates initial functionality, showcasing the framework's potential to streamline construction processes and enhance decision-making. By leveraging simulation and HLA synergies, our framework represents a promising approach to achieving integrated construction planning and control throughout project lifecycles.

1 INTRODUCTION

Construction project planning is the process of defining the objectives, scope, timeline, resources, and strategies required to successfully execute a construction project. It involves comprehensive analysis, coordination, and decision-making to ensure that the project is completed efficiently, within budget, and according to specifications. Once execution begins, effective monitoring and control are important to ensure that actual performance does not deviate from planned performance (Azimi et al. 2011). If this is the case, plans must be revised and corrective actions taken to ensure that the projects go back on track. Accordingly, the processes of construction planning and control are continuous throughout the lifecycle of the project. Network-based tools such as Critical Path Method (CPM), Program Evaluation and Review Technique (PERT), and Earned Value Method (EVM) are widely used in the A/E/C industry for planning and control. However, their static approach may yield unrealistic estimations making them inadequate for today's dynamic projects (Lee et al. 2006). As a result, computer simulation has emerged as a tool to address the uncertain characteristics of construction projects.

Through simulation models, users can grasp the logic and progression of various activities—as well as the utilization of resources—while also considering external factors such as weather, soil conditions, and traffic flow that may influence project execution (AbouRizk 2010). Furthermore, these models offer insight into the behavior of construction systems, enabling users to evaluate how they respond to different conditions and manipulate them to optimize performance (AbouRizk et al. 2016). This capability proves particularly beneficial during the project planning phase where diverse scenarios can be examined to devise near-optimal solutions that align with key project objectives. Previous research endeavors have delved into the application of simulation across various construction operations (AbouRizk and Halpin 1993; Al-Hussein et al. 2006; Lu 2003; S. RazaviAlavi and AbouRizk 2017; S. R. RazaviAlavi and AbouRizk 2022). Despite the advancements made in construction project simulation applications, the utilization of simulation models remains limited, primarily due to their inherent complexity.

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Indeed, the development of simulation models is often demanding and, once created, they tend to be overly specific to the problems-at-hand thereby limiting their reusability. Consequently, significant investments in time, effort, and expertise are required to tailor simulation models to particular issues. These challenges prompted researchers to explore alternative approaches to address these concerns. One such approach is the adoption of High-Level Architecture (HLA) standards, introduced by the US Department of Defense in the mid-1990s. HLA aims to integrate multiple autonomous simulations into a single, distributed simulation environment, fostering reuse and interoperability (Azimi et al. 2011; Kuhl et al. 1999). The underlying principle of HLA is the recognition that no single simulation can adequately fulfill all the needs and applications of a specific domain (Fujimoto 2003). By facilitating the integration of independent simulators, known as "federates," HLA enables the execution of distributed simulations termed "federations" (Gan et al. 2000). This structured approach not only promotes the reuse of diverse simulations but also works toward reducing the cost and time of creating synthetic environments for new purposes.

While HLA standards offer benefits like reusing and connecting simulations, applying these standards presents its own set of challenges. Firstly, understanding and following the technical specifications and protocols require considerable expertise, making it complex especially for those with limited experience with coding and computer science knowledge. Additionally, the learning curve associated with HLA can be steep for those unfamiliar with distributed simulation concepts, necessitating training. Secondly, bringing together multiple independent simulations into a cohesive environment, as required by HLA, is difficult. It involves ensuring smooth interaction among various simulation components, which often entails extensive setup and testing. Lastly, ensuring compatibility and compliance with HLA across different federations to allow reusability of simulation components is challenging and may lead to integration issues.

This study aims to create a federated data-driven simulation framework designed to address the challenges discussed above and ultimately achieve integrated construction planning and control. The research outcome is an automated simulation-based framework comprising standalone systems capable of interacting with one another according to the rules defined by the HLA standards. It will also include a standard object representation to which the data of participating systems can be mapped. The proposed platform aims to enhance construction planning and control by harnessing the advantages of simulation and HLA standards while overcoming the complexities that have previously limited their full adoption. Key features include the integration of real-time data gathering, information modeling, and data-driven decision support. Ultimately, this framework attempts to streamline construction processes, improve decision-making, and optimize project outcomes.

The remainder of this paper is organized as follows: Section 2 give a background on HLA. Section 3 presents the framework with its main components. Section 4 presents a prototype of the proposed framework with its limitations and the future work. Section 5 presents an overall summary of the work.

2 BACKGROUND

2.1 Construction Simulation

Simulation modeling is defined as the process of developing and experimenting with computer-based representations of real-world systems to understand and study their underlying behavior (AbouRizk et al. 2016). It has been successfully applied as a decision-support tool in several domains such as manufacturing, healthcare, and military. Given the dynamic and complex nature of construction projects, which involve multiple stakeholders, resources, and activities, researchers have found that simulation techniques offer the necessary analytical capabilities for effective planning and control of these projects (Abdelmegid et al. 2023).

Construction simulation has evolved significantly over the years, starting with Halpin's development of the CYCLONE (1977) simulation language in 1976. This early work laid the foundation for subsequent advancements, including the introduction of object-oriented concepts by Shewchuk and Chang (1991), which made models more intuitive and readable. Further developments, such as Shi's Activity-Based

Construction (ABC) language (1999) and AbouRizk and Mather's CAD-integrated approach (2000), have continued to streamline and enhance construction simulation modeling.

Key simulation tools in construction today include STROBOSCOPE, introduced by Martinez and Ioannou (1999), and Simphony by Hajjar and AbouRizk (2002). STROBOSCOPE and Simphony both utilize discrete-event simulation (DES), which is one of the most commonly used methods in construction simulation. These tools offer extensive customization and ease of use, making them suitable for a wide variety of construction projects.

Despite the prevalence of DES in construction simulation, its limitations have been acknowledged over the years. DES requires the discretization of continuous data, lacks the ability to incorporate feedback processes, and faces challenges in model verification and validation (Araya 2022). To address these issues, researchers have started integrating DES with other simulation techniques used in the construction field. These include agent-based modeling (ABM) (Abdelkhalek and Zayed 2020), system dynamics (SD) (Xu et al. 2018), and virtual environments (Abbasi et al. 2020).

Even with extensive research efforts, construction simulation still struggles with industrial adoption (Abdelmegid et al. 2023). Construction practitioners are often hesitant to use simulation modeling as a decision-support tool due to several factors. These include the steep learning curve associated with simulation modeling, the significant time and cost required for simulation studies, and a general resistance within the construction industry towards digital technologies (Abdelmegid et al. 2023).

2.2 High-Level Architecture (HLA)

The HLA was devised by the US Department of Defense to enhance simulation utility across diverse military applications while ensuring cost-effectiveness. Published initially in 1995 and finalized in 1996—with subsequent IEEE versions in 2000—HLA facilitates simulation reuse and interoperability (Dahmann 1997). Its broad applicability spans various sectors including education, engineering, and entertainment, without prescribing specific implementations or software, allowing for adaptability to evolving technological advancements.

Federates within an HLA federation can represent simulations which might include event-driven simulations, human-in-the-loop simulators, live equipment, data adapters, or interfaces to live players/facilities (Dahmann 1997; Dumond and Little 2003). HLA places no restrictions on federate representation but requires specified capabilities for interaction, facilitated by a common federate communications interface known as a Run-Time Infrastructure (RTI). This RTI serves as a centralized communication hub, supporting federate interactions and federation management functions, ensuring all interactions occur through it (Dahmann 1997; Kuhl et al. 1999). The HLA interface specification outlines the runtime services facilitated between federates and the RTI, encompassing the following six service classes: (1) federation management services that enable the creation and operation of federations; (2) declaration management services that optimize data exchange efficiency by specifying federate-provided and required data; (3) object management services that handle object-level operations like creation and deletion; (4) ownership management services that support dynamic ownership transfer during execution; (5) time management services that synchronize runtime simulation data exchange; and (6) data distribution management services that efficiently route data among federates. The specification dictates how these services are accessed both functionally and in a programmer's interface (Dahmann 1997; Kuhl et al. 1999).

The HLA object models serve as descriptions of essential shareable elements within simulations or federations, articulated in 'object' terms. HLA emphasizes focusing object models on critical simulation and federation aspects shared across a federation without imposing content constraints for the purpose of promoting interoperability. The HLA also specifies two types of object models: the HLA Federation Object Model (FOM) and the HLA Simulation Object Model (SOM). The FOM delineates shared objects, attributes, and interactions across a federation, while the SOM outlines a federate's capabilities for future federations, serving as a contract defining the information it can offer. While the HLA does not prescribe specific SOM or FOM contents, it mandates a standardized documentation approach using the HLA Object Model Template (OMT) for both (Dahmann 1997; Dumond and Little 2003). For more information on the

HLA standards and rules, the reader is referred to (Simulation Interoperability Standards Organization/Standards Activties Committee [SISO/SAC] 2010).

3 AUTOMATED SIMULATION-BASED FRAMEWORK

According to Halfawy and Froese (2007), an integrated project system must support three basic requirements: (1) integration of large amounts of project data and documents throughout the project lifecycle; (2) integration of various project processes; and (3) a standard data model to allow various applications to plug into the system and interoperate and exchange data with other applications. The proposed environment, illustrated in Figure 1, is structured into three key components to achieve full system integration as outlined by Halfawy and Froese (2007).

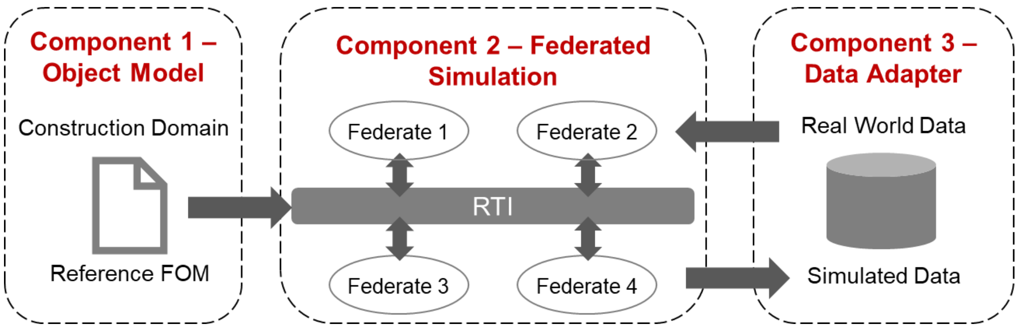

Figure 1: Conceptual framework.

The first component entails a standard FOM tailored specifically for construction operations. This component facilitates interoperability and reusability of construction simulations and establishes a benchmark for future federates. By adhering to this standard, future federates can seamlessly integrate into the federation, avoiding the need for extensive FOM development efforts. The idea behind a standard FOM is motivated by the existence of two commonly used reference FOMs for defense and space simulations: the Real-time Platform FOM (RPR-FOM) and SpaceFOM.

The second component comprises the standard federated simulation model. This component is useful for project planning and control, offering a high-level perspective primarily through network-based approaches, aligning closely with prevalent industry practices.

Lastly, the third component encompasses a data integration mechanism. This component consolidates data from real-world sources including sensors, information systems, and reports, enriching the federation's dataset. Additionally, it manages simulated data generated by the federation, storing it for scenario analysis and decision-making processes thereby enhancing the framework's efficacy and versatility. The next sections provide a more detailed overview of the three components.

3.1 Construction Federation Object Model (Con-FOM)

To enable effective communication and information exchange among federates, an FOM must be specified. Often termed as "the language of the federation" (Möller et al. 2014), the FOM encompasses critical elements such as object classes, attributes, interaction classes, parameters, and datatype definitions. Developing a comprehensive FOM poses a significant challenge in distributed simulation, requiring extensive research efforts to interlink computer simulations representing discrete physical entities within virtual environments (Kuhl et al. 1999). The absence of a well-defined standardized FOM has impeded the construction industry's ability to fully capitalize on the advantages offered by the HLA.

A common approach to address this challenge involves leveraging standardized FOMs—often referred to as reference FOMs—and tailoring them to specific project or program requirements. This practice yields numerous benefits including time and cost savings as insights and lessons from previous projects can be readily applied. Furthermore, utilizing reference FOMs mitigates risks, given their performance and established success in past federations. It also enhances the ease of reusing simulations supporting these reference FOMs in new combinations. Since these simulations are already equipped to exchange data in a compatible manner, integrating them into diverse contexts becomes simpler and seamless (Möller et al. 2014).

Two well-developed reference FOMs are the RPR-FOM (RPR FOM Product Development Group 2015) and SpaceFOM (The SpaceFOM Product Development Group 2020). The RPR-FOM is the most commonly used FOM for defense simulations and focuses on simulations of war-fighting scenarios including humans, weapons, and platforms (Möller et al. 2014). The SpaceFOM was developed to allow users to create HLA-based federates in the space domain while guaranteeing a-priori interoperability. It builds on the RPR-FOM by providing enhancements tailored to the needs of space simulation, addressing limitations inherent in the RPR-FOM. These include accommodating diverse coordinate systems relevant to celestial bodies beyond Earth, implementing robust time management mechanisms consistent with HLA standards, and expanding the range of object classes to encompass key aspects relevant to space domain simulations (Crues et al. 2022).

This being said, the first step in the illustrated framework above is to create a standardized FOM designed for the construction domain. This aims to improve interoperability among different federates, ensuring they can seamlessly work together and meet the specific needs of the simulations for which they are intended.

3.1.1 Overview

The Construction Federation Object Model (Con-FOM) is designed to facilitate interoperability among simulations in the construction domain. The primary intended applications include training, conceptual testing and exploration, and analysis, and the advantages of the Con-FOM are as follows:

- Interoperability: Multiple simulations with specific tasks (e.g., site progress monitoring, risk management, equipment operations, and site layout planning) can collaborate and collectively create a simulation with broader and more comprehensive contexts.
- Composability: Simulations can be constructed by combining components in various ways—allowing for the creation of collaborative simulations that serve specific objectives—using both new and existing simulations.
- Reusability: Existing simulations can be utilized in new contexts. The Con-FOM facilitates the development of generic and reusable federates and tools tailored to the construction industry.

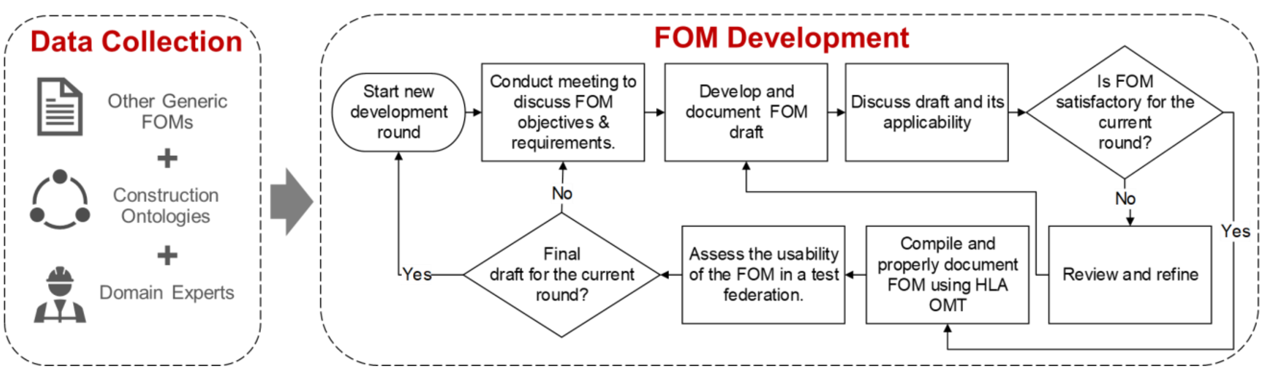

Figure 2: FOM development.

Figure 2 illustrates a typical round of development for the standardized Con-FOM. It begins with comprehensive data collection from various sources including existing reference FOMs (specifically the

RPR-FOM and SpaceFOM), construction ontologies, and insights from academic and industrial experts. This stage helps define the Con-FOM's purpose, scope, objectives, and requirements. Object classes representing entities in the simulation and their attributes are then identified, ensuring global representation within the simulation environment. More detailed information on this aspect is provided in upcoming sections. Subsequently, the process involves determining suitable datatypes for the attributes to facilitate data exchange and communication among simulation components. Throughout the process, the FOM is thoroughly documented, detailing its structure, relationships, and attributes.

3.1.2 Object Class Definition

Advanced Work Packaging (AWP) is a project management methodology, developed by the Construction Industry Institute (CII) and Construction Owners Association of Alberta (COAA), that helps plan, execute and control construction projects by breaking down the work into smaller, manageable pieces known as work packages (ElMenshawy et al. 2023). Work packages are a fundamental part of AWP and are defined as self-contained, executable tasks that include all information and resources needed to complete the work (CII and COAA 2013). The CII and COAA have jointly developed guidelines for creating work packages based on the AWP concept. According to these guidelines, a work package should include the following components:

1. Scope of Work: A concise description detailing the work to be performed including expected outcomes and quality standards.
2. Deliverables: A comprehensive list outlining tangible and intangible items expected upon work package completion.
3. Schedule: A detailed plan encompassing start and end dates, along with milestones and deadlines.
4. Resources: All necessary resources including personnel, equipment, materials, and tools.
5. Budget: Estimation of costs associated with the work package covering labor, materials, and other expenses.
6. Risk Assessment: A thorough evaluation and management plan for potential risks.
7. Quality Assurance: Ensuring adherence to quality standards and meeting specified requirements.
8. Communication Plan: Establishing effective communication with all stakeholders involved in the work package.

Overall, a work package—as per AWP principles—is envisioned as a well-defined, self-contained unit encompassing all essential information, resources, and plans required for successful completion. In addition to the AWP-based definition, Zheng et al. (2021) introduced a digital construction ontology (DiCon) aimed at modeling construction workflows in an attempt to integrate information from various sources across multiple contexts. Drawing from the lean construction's activity flow model (AFM), they define construction activities as “assembly type operations that are enabled by a variety of ingredients called ‘flows,’ including labor, equipment, workspaces, components, information, external conditions, and prerequisite tasks” (Zheng et al. 2021). Within the DiCon ontology, several classes are established, including project, activity, equipment, resource, service, and organization, providing a comprehensive view of the construction workflow. By leveraging both the AWP-based work package concept and the DiCon ontology, the object classes for the Con-FOM can be defined. The resulting object class hierarchy is depicted in Table 1, with further insights provided in the subsequent section.

Regarding the developed object classes, *WorkBlock* encapsulates specific tasks to be accomplished, incorporating attributes related to scheduling, budgeting, progress, and location. It is closely linked to *WorkSpace*, defining the area where work takes place but also capturing other project site areas including temporary facilities and material storage areas. *ResourceBlock* outlines resources necessary for task execution such as labor, equipment, or materials. Attributes within *LaborResource* provide insights into factors like production rate, experience level, and learning rate. Similarly, attributes within *EquipmentResource* cover details like equipment type, model, maintenance schedule, and last maintenance date. *WorkBlock*, *WorkSpace*, and *ResourceBlock* derive from *Hierarchy*. This allows users to define levels for each. For example, the highest level of *WorkBlock* represents the entire project. This can be further decomposed into smaller *WorkBlocks* depending on the level of detail required by the user. *Constraints* and its subclasses play a crucial role in work commencement, ensuring necessary conditions are met. *Constraints* also defines these conditions and creates smooth workflow progression. Finally, *SafetyRisk* tracks safety incident data including both fatalities and non-fatalities while *Environment* includes attributes related to external conditions impacting work such as temperature, humidity, and wind speed. These elements collectively contribute to a comprehensive representation of the work environment within the Con-FOM.

Table 1: Object class hierarchy.

HLAObjectRoot	Hierarchy	WorkBlock	
		WorkSpace	
		ResourceBlock	LaborResource
			EquipmentResource
			Material
	Constraint	LogicalDependency	
		Permit	
		Drawing	
		Specification	
		ChangeOrder	
		Rework	
	SafetyRisk	Fatality	
		Non-Fatality	
	Environment		

It is important to highlight that FOMs can be extended based on the specifications outlined in HLA (Simulation Interoperability Standards Organization/Standards Activties Committee [SISO/SAC] 2010). This means that if the existing FOM needs additional features to function within a specific federation beyond what is currently described, those extensions can be incorporated. It is also worth noting that this FOM serves as a foundational framework, significantly reducing the time and effort needed to construct new federations for construction operations.

3.2 Federated Planning and Control Simulation Model

Previous attempts in the construction domain have aimed to develop simulation models to integrate planning and control processes. However, these efforts have often fallen short in achieving comprehensive integration and self-adaptability (Labban et al. 2021). By leveraging the standard Con-FOM and HLA specifications, the gaps identified from previous research can be effectively addressed. This federated simulation approach offers a promising solution, wherein the simulation model is automatically generated based on input data from the construction site. The model is then executed, and as real-time information becomes available, it is dynamically updated.

In addition to this dynamic, data-driven approach, adhering to a standard FOM facilitates the incorporation of plug-and-play flexibility and modularity within the federation. This means that the simulation functions are broken down into several federates, allowing for flexibility in choosing which federates participate in the federation. For example, a federate modeling weather using historical data could be easily unplugged from the federation and replaced by a weather federate modeling weather stochastically without the need for modifying the rest of the federation. Moreover, federates can be replaced or added as needed, adapting to the specific requirements of the project. This flexibility ensures that the federation can seamlessly integrate various components and effectively respond to changing project conditions.

3.3 Data Integration

The third component of the framework, illustrated in Figure 3, is required for seamlessly integrating heterogenous information from various sources, including sensors, reports, and company information systems, into the federation. It also incorporates a database to store this vital information. The integration of such data into the federation enables simulation models and future forecasts to accurately reflect evolving conditions on the construction site, and provides the architecture to enable users to experiment with different scenarios and study their outcomes by keeping track of input and output parameters.

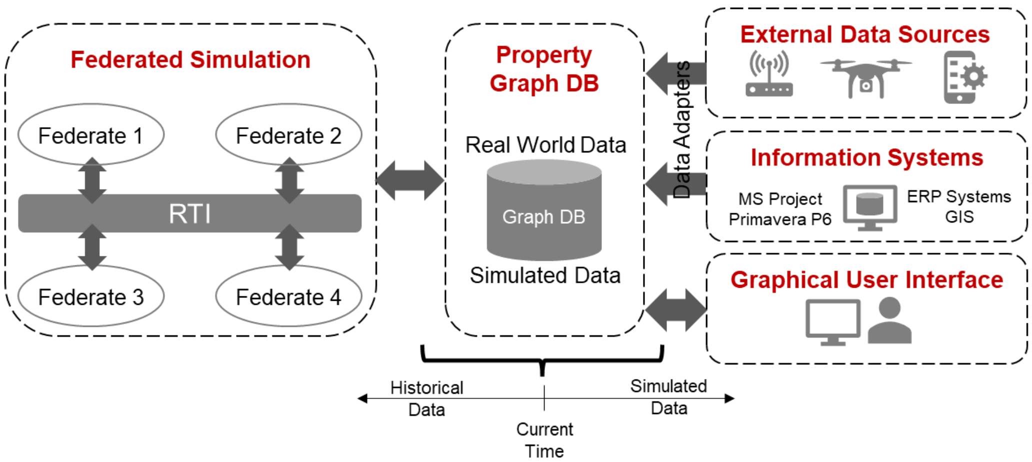

Figure 3: Data integration component.

A recent study by Ramonell et al. (2023) explored the use of knowledge graphs as a means of achieving modular, flexible, and interoperable data integration. Knowledge graphs utilize graph-based data structures, emphasizing contextual understanding by interlinking metadata. This approach proves ideal for applications requiring the integration, management, and extraction of valuable data from diverse sources at scale (Ramonell et al. 2023). The study highlights several advantages of knowledge graphs over traditional data models. Notably, they excel in modeling, structuring, managing, and analyzing heterogeneous and complex data with dynamic relationships, as well as offer the flexibility to evolve without the need for predefined schemas (Ramonell et al. 2023). Building upon these findings, this research aims to leverage knowledge graphs stored in a property graph model to achieve the objective of data integration and storage within the framework. This approach aims to enhance the adaptability, flexibility, scalability, and effectiveness of the data integration component thereby facilitating seamless integration and utilization of diverse data sources for informed decision-making in construction operations.

4 PROTOTYPE FEDERATION

The described framework was tested through a prototype federation, shown in Figure 4, to assess its practicality and viability. While some features—like automatic data acquisition and integration—are still undergoing development, the functionality of other components was successfully tested. The project used for testing is an actual industrial project. Only a portion of the project was used consisting of 51 work packages.

The prototype federation consists of six federates: planner, progress, safety, weather, visualizer, and dashboard. Initially, the planner federate compiles a list of all project *WorkBlocks* and conducts CPM calculations. It then assigns resources for the project's first day and shares this data with the federation. Subsequently, the progress federate assesses whether the assigned *WorkBlocks* have satisfied certain hard constraints to be able to progress for the day. It considers factors like weather conditions from the weather federate and safety incident updates from the safety federate, alongside other constraints and uncertainties, to calculate daily progress rates. This progress data, in terms of percent complete (PC), is fed back into the federation. This iterative process continues until all *WorkBlocks* reach 100% completion. During this time, the visualizer federate offers a 3D visualization of the project, illustrating its progress on a 3D model. Additionally, the dashboard federate delivers high-level project metrics such as the cost performance index (CPI), schedule performance index (SPI), and project percent complete (PPC). These metrics serve as an overview for users, aiding in decision-making.

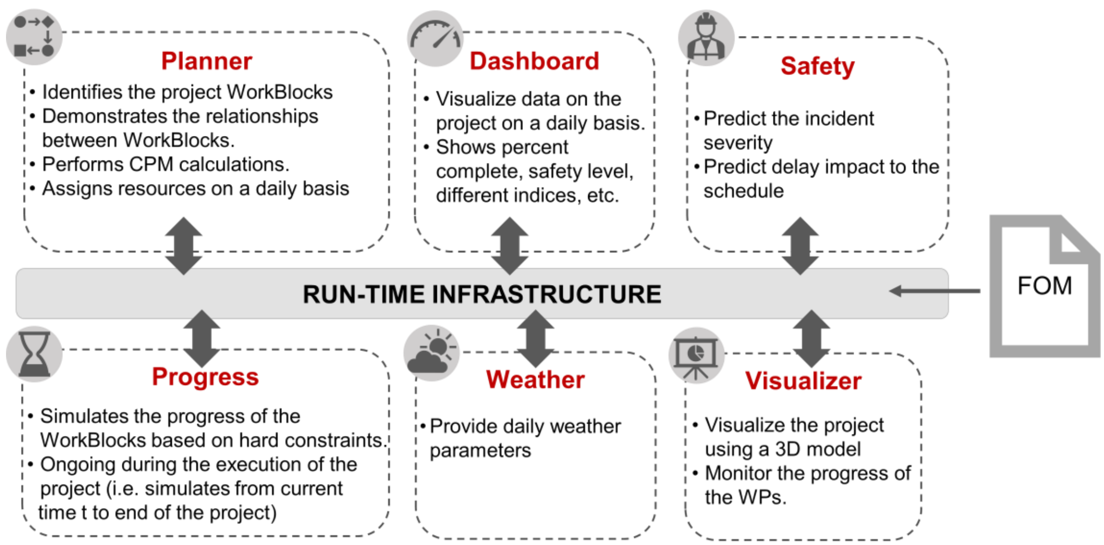

Figure 4: Prototype federation.

This initial version of the federation served as a valuable platform for the authors to explore and implement fundamental concepts of the HLA by enabling hands-on exploration of crucial aspects such as creating and operating the federation, ensuring synchronized data exchange between federates, instantiating object classes, and facilitating the publication and subscription of attributes. Furthermore, the federation provided a practical environment for experimenting with time management within the simulation context. This practical experimentation not only facilitated a deeper understanding of simulation features but also provided insights into the necessary steps for refining and advancing towards the final conceptual framework outlined earlier. It served as a foundation for identifying areas of improvement and guiding future development efforts toward achieving the desired objectives of the framework.

4.1 Verification and Validation

To ensure the accuracy of the simulation, we employed verification and validation techniques which were crucial for the reliable application of the proposed method, as decisions are based on these results. For model verification, it was essential to confirm the correctness of the code generated using C#, a higher-level programming language. According to Sargent (2011) higher-level programming languages have a higher likelihood of errors compared to special-purpose simulation languages. Therefore, the verification focused on "determining that the simulation functions and the computer model have been programmed and implemented correctly" (Sargent 2011).

Simulation testing can be performed using static or dynamic testing approaches. For this experiment, verification was primarily conducted using dynamic testing. This involved altering the model's variables and analyzing the resulting values to ensure the development and implementation were accurate. Specific techniques included manually tracing the output to verify all calculations, comparing the output with basic results from the Microsoft Excel model, and performing sensitivity analysis to validate the relationships between inputs and outputs

4.2 Limitations and Future Work

There were, of course, some limitations to the prototype federation. As noted, not all aspects of the framework were thoroughly tested during this initial implementation phase. Although the federation utilized XML documents to store project data, the ultimate goal is to develop an automatic data acquisition, integration, and storage component. This component would enable continuous updating of simulation models throughout the federation's runtime. Furthermore, the concepts of simulated planning and control were tested here, but the simulation models require further refinement and enhancement to provide more realistic forecasting outputs for decision-making purposes. This case study also primarily revolved around experimenting with HLA features, with less emphasis on user experience. The authors recognize that further enhancements are necessary to improve user experience, particularly for project managers utilizing the framework. This entails developing a user-friendly interface and incorporating features to enable human-in-the-loop interactions with the federation for scenario analysis and decision-making purposes. Finally, the authors identified the importance of a "master federate" for the efficient functioning of the federation. The concept of a master federate, introduced in the SpaceFOM (Crues et al. 2022), entails responsibility for high-level coordination of the federation execution. It facilitates federate role determination, coordinates the initialization process, and manages late-joining federates.

5 CONCLUSION

This paper presents a comprehensive framework for integrated planning and control in construction projects through the development of a novel federated simulation approach. By combining the benefits of simulation technology with the HLA standards, the proposed framework offers a promising solution to address complexities and challenges inherent in construction project management. The framework addresses the limitations of traditional planning and control methods by leveraging the flexibility and adaptability of federated simulations. It provides a standardized environment where various simulations can seamlessly interact, enabling real-time decision-making and scenario analysis throughout the project lifecycle. Through the standardized Con-FOM, interoperability, composability, and reusability are enhanced, facilitating plug-and-play flexibility and modularity.

Furthermore, the prototype federation demonstrated the practicality and viability of the proposed framework, showcasing its potential to streamline construction processes and improve decision-making. Although certain aspects of the framework—such as automatic data acquisition and integration—require further development, the initial implementation served as a foundation for future refinement and enhancement. Looking ahead, future work will focus on refining simulation models, improving user experience, and incorporating features for human-in-the-loop interactions. The concept of a master federate will also be explored.

Overall, the proposed federated simulation framework represents a significant advancement in the field of construction project management, offering a holistic approach to integrated planning and control. By leveraging simulation technology and HLA standards, it has the potential to revolutionize how construction projects are planned, executed, and monitored, ultimately leading to improved project outcomes and increased efficiency in the construction industry.

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