Complementarity and Compatibility of Systems Integration and Building Information Management

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***Abstract*—The introduction of building information management (BIM) to enable the management and delivery of megaprojects has illuminated the importance of system integration (SI) to coordinate and bring together complex interdependent technical and organizational systems. SI can inform and address the emerging interdependencies with BIM processes and technologies in megaprojects. Thus, in this article, we extend the theorizing of SI and BIM for the management of megaprojects in the infrastructure sector. This process involves 1) conceptualizing the complementarity and compatibility of SI and BIM in the management of megaprojects, and 2) offering an integrative framework and model of SI and BIM. Finally, we discuss and highlight this twofold contribution and offer insights into future research.**

***Index Terms*—Building information management (BIM), complexity, infrastructure, management of megaprojects, system integration (SI).**

I. Introduction

DURING the last decade, there has been a marked increase in the scale and pace of change in infrastructure megaprojects [1]. While previously megaprojects were discrete and constrained, they have become open, complex, and highly uncertain [2], [3], [4]. Megaprojects are temporary models for the delivery of physical infrastructure used to create value for the society and economy but they themselves require large investments [1]. Megaprojects are typically associated with high complexity and uncertainty inherent in the numerous independent networks that lack visibility [1]. Management of infrastructure megaprojects requires new governance models based on systems engineering and integration principles [5] across the entire lifecycle of the system [6]. Thus, in recent years, management of complex megaprojects with system integration (SI) [3], [7] and separately with building information management (BIM) [8], [9] has gained importance to tackle the issues of complexity and uncertainty [3], [10].

SI and BIM are dominated by theoretical conceptualizations that are not only complementary but also overlap. SI offers logical and behavioral instantiations of information management underpinned with a strong theoretical basis of systems thinking and approaches [7], while BIM offers cyber-physical management of information with the use of digital technologies and processes that require development of theoretical underpinnings with systems approaches [8]. Despite their complementarity and compatibility, these different perspectives evolved and were implemented separately in literature and practice. As a result, this theoretical article aims to study SI and BIM together and proposes an integrative framework and the corresponding model. It is further argued that SI and BIM are complementary and compatible and reinforce each other if implemented in an integrated way.

There is an emerging discourse on the use of SI and BIM in megaprojects [10], [11], [12], [13], [14] that has not resulted yet in a strong theoretical basis for future research. This work offers two contributions. The first contribution is the conceptualization of SI and BIM complementarity and compatibility for the management of megaprojects. The second contribution is the combination of BIM and SI into one theoretical integrative framework. Taking on board previous literature and our practical experiences, this framework presents a first effort in theorizing about SI's and BIM's compatibility and complementarity. The framework makes explicit the areas of complementarity and offers the theoretical and practical basis for future research. It strengthens the existing theories on BIM that were predominantly, and yet indirectly, seeking a systems approach, inherent in SI methodology. We expect that this framework could constitute an important contribution to the literature on SI and BIM that will allow scholars to explore and build upon it as a foundation for future research.

II. SI and BIM Conceptualizations

SI and BIM evolved as two separate streams in the literature: SI to deal with and manage emergent complexities and ambiguities in megaprojects in the infrastructure sector [3], [7], [15] and BIM as an important agenda to transform the design, construction, and operation industry with the use of digital information modeling processes and technologies [8], [9]. Both streams offer valuable methodologies for the management of megaprojects. It is important to note that BIM was used predominantly in the building industry, while SI was adopted widely in the complex infrastructure sector.

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A. SI Conceptualizations

The notion of SI arose in the mid-20th century through work on systems engineering. Systems engineering emerged from the need to deliver complex projects in the USA military and aerospace industries [16].

Over the last two decades or so, due to the growing number of infrastructure megaprojects across the globe, considerable attention has been devoted to SI as a means for managing megaprojects [3], [17]. Infrastructure megaprojects deliver complex product systems [9], [13], which are considered "complex adaptive systems" [18], and often exhibit unpredictable emergent system behaviors [18]. Infrastructure megaprojects are of significant scale, with long durations, and require integration across organizational boundaries [20]. Thus, they are challenged with the integration and management of highly complex and numerous interdependencies [21]. Lack of integration in megaprojects produces inadequate information that can lead to higher risks associated with the unpredictability of system behavior [22].

In recent years, a new stream of research on SI for the management of megaprojects in the infrastructure sector has emerged [3], [22]. Whyte and Davies [3] suggest SI as the process of making constituent parts of systems work together, which aligns with the systems engineering definition provided by the SEBoK [7].

SI can guide the system development following bottom-up and top-down approaches. The bottom-up approach is guided by systems engineering, it coordinates and manages requirements at a subsystem level across the specialist teams, rather than at a system level (i.e., system decomposition). For example, systems, and their functions, behaviors, and structure can be considered bottom-up if some components of the system of interest were inherited and their function cannot be changed regardless of the wider system development. A bottom-up approach to SI typically combines performance models and the use of specific tools such as the design structure matrix [23]. On the one hand, a top-down approach imposes compliance with standards at the interfaces between the product and work breakdown structures. On the other hand, model-based systems engineering (MBSE) [24], [25] for instance, provides an approach for top-down consideration of systems [22]. MBSE is the formalized application of modeling to support system requirements, design [24], analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle phases [27]. Building information modeling processes are aligned with MBSE in terms of ontologies and modeling processes [28]. Both processes start by defining ontologies (essentially a representation of the system components at a macro-level) thereby creating a common understanding of definitions and how the system will be designed and built to support requirements, design, analysis, verification, and validation activities throughout the lifecycle of the system of interest.

As deliverables of infrastructure megaprojects are becoming increasingly cyber-physical and incorporate virtual and physical models of the system, digital information is becoming a project deliverable in itself; a valuable digital asset, changing the supply chain interactions and relationships with owners, operators, and end users [10].

There is an opportunity to advance the understanding of how SI is enacted through the use of new digital forms of megaproject organizing [3]. The SI literature has called for an advanced understanding of how new emerging processes with digital tools and techniques can aid SI in terms of visualization, integration, analysis, verification, and validation of highly interdependent entities for the management of the infrastructure megaprojects throughout the lifecycle of the system of interest [3], [10], [22].

B. BIM Conceptualizations

Since the seminal work of Eastman [29], building information models were proposed to the design and construction industry as a totally new way of information management. These models were distinguished from the traditional two-dimensional-based computer-aided design (CAD) processes in terms of the functional and geospatial arrangement of digitally and three-dimensionally designed components with the use of digital technologies and collaborative processes [8]. BIM implementation aims to tackle the persistent issues of waste, slow deliveries, high costs, and lack of safety in construction practices associated with the high levels of fragmentation of the industry and the fragmented ways of project delivery with the lowest bid as a procurement rule [30], [31].

In the building sector, BIM (taken comprehensively) is considered a novel technology, despite its use in design for several years. It comprises concepts and methods as well as a set of technologies and processes constituting a methodology. Ultimately, BIM offers a totally new way of information management throughout the lifecycle of a building project and the subsequent system.

There are variations in definitions and terms across individuals, organizations, and countries. BIM as an abbreviation is often used to refer to three related concepts. BIM has been referred to as building information modeling [8], building information model [32], and BIM [33]. All three terms are used interchangeably as they are interrelated and complementary.

BIM, essentially, incorporates organizational and technical aspects of information management used to enable interorganizational value creation with digital models and is a socio-technical construct. Despite the existing emphasis on the technical aspects of BIM, the social and organizational aspects of BIM processes have proved to be critical but remained a challenge for integration [9], [33], [34].

Interorganizational collaboration with BIM provides value to clients and their businesses but also proves to be challenging from a realization and wide implementation point of view. Specifically, these challenges are related to established project processes, inferior integration across teams and systems, as well conservative attitudes and mindsets [32], competency management [35], education [36], leadership and management of megaprojects associated challenges, such as contracts, governance, workflows, and colocation.

Although digital technologies are changing project delivery from paper-based documentation towards digital information [9], there has been limited evidence of "true" information integration across projects, organizational boundaries, systems, and throughout the lifecycle of built assets [35]. Empirical evidence has further justified the need for systems engineering management to enable integration with BIM [10], [11] and to address the inherent issues of fragmentation of megaprojects and industry [36].

III. SI and BIM Complementarity and Compatibility Framework

A. Motivation

The introduction of digital tools and processes for the management of megaprojects, specifically the digitalization of formerly manual processes, records, and products, has led to a profound shift in the way megaproject actors handle data and manage information throughout the lifecycle of a system of interest [39]. In response to this change, we have seen an increase in the use of SI for the management of requirements throughout the system of interest lifecycle (e.g., infrastructure, IT, telecoms) and BIM processes for the management of information (e.g., buildings, infrastructure, utilities). Although SI and BIM are both used to manage information throughout the product lifecycle, they have been implemented separately and are two separate streams of literature with little cross-fertilization and discussion of their compatibility and complementarity.

However, SI and BIM are theoretically and practically complementary and compatible for implementation in megaprojects because the built assets (represented digitally with the use of building information models) include a vast array of systems and subsystems (represented in system architectures). In megaprojects, the two processes run in parallel with each other, yet there is no evidence in literature and practice that SI and BIM have been implemented in tandem. Currently, we do not find sufficient evidence of their formalized alignment in literature or practice. This situation demands nuanced attention because SI's focus on integrating information throughout the lifecycle of a system of interest has many theoretical and practical overlaps with BIM in terms of information management. SI and BIM are complementary and compatible as the underlying foundation of information architecture. We identified three overlaps.

1) The domain of SI, specifically systems architectures, which are the logical and functional architectures, drive the allocation of physical subsystems and geospatial arrangements in the domain of BIM.
2) SI and BIM are both driven by requirements defined at system-of-systems, systems, and subsystems levels with different degrees of information granularity in SI, while BIM embodies the development of a system architecture and disciplinary models by delivering subsystems and components (architectural, engineering, MEP, etc.).
3) SI and BIM provide integration of complex systems from the lowest subsystem and components to the highest idealized output of the system.

We identified a need for a theoretical framework that combines SI and BIM to provide insights into interactions in the management of megaprojects. It should provide the basis for scholars to research the changing relationships, roles, and processes in the management of megaprojects with evolving digitalization in the context of the infrastructure sector. In Section III-B, we present the micro-foundations of the proposed integrative framework of SI and BIM.

B. Microfoundations of the Framework

In the previous sections, we established that SI and BIM have evolved in isolation, while both are complementary and share parallels in conceptualizations, methodologies, and practices. To develop a framework, we present microfoundations based on our analysis of the existing literature and practical experiences in megaprojects. Table I presents a set of micro-foundations that make up the SI and BIM methodologies for the management of megaprojects.

Our analysis of microfoundations, presented in Table I, illustrates compatibilities in terms of overlaps and parallels between SI and BIM.

Level of analysis: SI focuses on definitions and developments of the system of interest while BIM focuses on the definition and development of the subsystems and its constituent components with digital processes and technologies. SI and BIM, both address adjacent levels of granularity of the system design. Architectural forms are defined as system architecture rather than a discipline of an architectural design.

Strategic objective(s): SI and BIM have complementary strategic objectives defined at their respective levels of analysis of the system and subsystem levels. While SI informs a system-level integration into a system-of-systems, BIM as a process is applied to the development of subsystems and its components in a form of the disciplinary information models that are developed by the disciplinary roles. The strategic objectives of SI guide the strategic objectives of BIM processes for a system-level integration.

Actors: The actors and their roles are well-defined in literature and practice. Considering that the roles in megaprojects have evolved in the recent years, the roles of actors and their tasks reflect the continuum that requires a certain level of adaptation and specialization. The actors and their roles are complementary in megaprojects. System integrators manage SI processes and BIM managers manage BIM processes.

Activities: Management activities refer to the nature of the tasks carried out in each discipline. Ultimately, they contribute to the management of the megaproject. SI and BIM are implemented side by side at different levels of detail and abstraction, while they manage information at different levels. They are both based on an architectural model with a strong emphasis on the embodiment of requirements and the subsequent verification and validation (V&V) of megaproject outcomes as a result of the satisfaction of those requirements.

Artifacts: There is a divergence in the nature of artifacts produced by SI and BIM. SI artifacts are a combination of visual representations (e.g., architecture and interface models) and textual

TABLE I
SI AND BIM FRAMEWORK MICROFOUNDATIONS

	SI	BIM
Level of analysis	System	Subsystem and components
Strategic objectives	Modeling Coordinating Analyzing Visualizing Designing Integrating Verifying	Modeling Coordinating Analyzing Visualizing Designing Integrating
Actors	System Integrator Requirements Manager System Architect Interface Manager Integration Manager Test Manager Designer	BIM Manager BIM Coordinator BIM Technician Designer Surveyor
Activities	Requirements management (system, subsystem) Architecture management (logical, functional, physical) Interface management (physical, functional, contractual) Integration management (system, sub-system) Verification and Validation (system, sub-system) Test (system)	Requirements management (sub-system, component) Architecture management (functional, physical, parametric, spatial) Interface Management (physical, functional, contractual) Integration management (subsystem) Verification and Validation (subsystem) Test (subsystem)
Artefacts	CONOPS Requirements database System Architecture Interface matrix and management plan, Interface Control Document (IDC) System Description Verification and Validation Matrix, Operational models Integration Management Plan, Test Plan / Script / Report	Disciplinary information models and architectural representations BIM execution plan CDE
Tools	Requirements management (e.g., DOORS) System Architecture management (e.g., EA) Interface Management (e.g., Relatics) Operational modelling (e.g., RailPlan, ProPlan) Test Log Management (e.g., JIRA) Verification & Validation Matrix Management (e.g., via DOORS Requirements Management tool)	Design management (e.g., ArchiCAD, REVIT, Tekla, Microstation, Navisworks) Geospatial integration (e.g., ArchiCAD, ArcGIS) Human-centered modelling (e.g., passenger flow modeling, smoke flow modeling)

representations [e.g., requirements databases, concepts of operations (CONOPS)]. BIM artifacts are mostly digital information models that represent geospatial design. This convergence is explained by the nature of the abstraction they aim to develop. SI abstractions are typically at a strategic level. They include the system description (or System of Systems [5] Description) and the concepts that underpin the system development (e.g., the concept of operations, concept of maintenance). These descriptions and concepts are precisely and richly described in textual form, whereas the BIM-level abstractions of detailed geospatial and physical designs are precisely and appropriately described in a diagrammatic form of blueprints derived from the coordinated information models.

Tools: SI and BIM tools are different in their presentations, but conceptually complementary, as both deal with information using ontologies. "An ontology is a specification of a conceptualization" [40]. Ontology defines a specification of a representational vocabulary including classes, functions, and their relationships within a specific domain of discourse [40]. Whilst information representation is different, SI and BIM reflect abstracted layers of the system of interest. SI tools typically focus on the development of logical architectures or representations of the system, which may or may not be aligned with the physical or contractual breakdown structure. SI tools may include requirements management, system architecture, or interface management tools. BIM tools typically focus on the physical and geospatial architecture of the subsystems and represent it as a constructed information model. BIM tools may include GIS tools or design packages for engineering design. The scope of work depends on the technical specification and often on the project management approach, organizational capabilities, and team competencies. Tools vary from megaproject to megaproject, depending on the team and project needs. Examples of tools have been included in Table I for demonstration purposes, and do not aim to offer an exhaustive list nor prioritise specific tools.

C. Conceptualization of the Framework

The compatibility of SI and BIM is demonstrated by the complementarity of its microfoundations as well as underpinnings that overlap theoretically and practically. Table II depicts relevant theoretical underpinnings. In the rest of the present section we present the SI and BIM complementarity and compatibility framework through theoretical underpinning that compose the framework (see Table II).

Theory: Starting from theoretical underpinnings, SI uses systems theory as the foundation for understanding technical, architectural, and organizational systems [3], [7]. Systems theory shapes the language used by SI specialists for communication and collaboration. On the other hand, we find no substantial evidence of a theory in the BIM literature. BIM language is shaped largely by industry dynamics, a firm's culture, and practices rather than theoretical and academic development. BIM can benefit from a systems language that might model and direct the approaches for the use of BIM for subsystem design that is currently present neither in literature nor in practice.

TABLE II
SI AND BIM COMPLEMENTARITY AND COMPATIBILITY FRAMEWORK

		SI	BIM
	Theory	Systems theory language	None
	Approach	Top-down	Bottom-up
	System levels	System, subsystem	Sub-system, component
	View of systems	Systems, subsystem , and components	Digital information models of sub-systems and components
	Emergent properties	System behavior	Subsystem behavior
	Interfaces	Interfaces can be anything (standards, space, etc.)	IFC, technical, and organizational standards define how interfaces are enacted (open and closed, technical, technological) (e.g. industry, corporate)
	End-users	Strength, strongly considered in a design of a system of interest	Weakness, not considered in BIM designing beyond specific applications
	Requirements management	Fundamental to SI	Treated separately but is influenced by
	Design	Implicit with abstraction of physical components	Explicit with as-modelled and as-built information
Governance	**Coordination via**	Requirements management and system architecture	BIM processes
Governance	**Capabilities**	Supply chain capabilities	Firm/discipline capabilities, disciplinary roles, and capabilities
Governance	**Governing body**	Systems Integrator	BIM manager
Governance	**Value processes**	Value articulation, creation, and capture	Value creation
Governance	**Core activities**	Facilitating, guiding, enabling, coordinating	Enabling, coordinating

SI is using decomposition as a process of breaking down outcome-based or strategic requirements and allocating them down to the lowest desired levels of system(s). BIM, however, follows the opposite sequence, by building up a federation of disciplinary information models that incorporate an array of components making up subsystems. Thus, SI adopts a top-down approach whereas BIM adopts a bottom-up.

The V-model is a graphical representation of a systems development lifecycle, which has been used in systems engineering to assist in a structured and logical development of the megaproject steps with the corresponding deliverables [7]. The V-model indicates that the system is defined before the system requirements are developed, see Fig. 1. Cascading down the V-model from the system to the subsystem and components levels, the discrete system elements gain increasing amounts of design-led validation evidence and levels of detail as the process follows the V-model. Information granularity also varies depending on the level and megaproject phase. We have adapted the V-model to overlay the systems engineering steps (numbered in boxes) with the BIM steps (in grey highlight).

While the V-model is a basis for SI, BIM processes are present in steps 5–11. Thus, BIM provides subsystem and component design (i.e., *System levels*, Table II) following the system architecture, as defined and led by SI in the front end of megaprojects. Building information models are delivered during the design phases and updated during the construction processes if they are not used for manufacturing (e.g., modular construction). As clients increasingly require the building information models as a deliverable for the use for facility management and operation, BIM, as a process, delivers asset information models that are as-built and as-required project information models. Therefore, the update and use of models for facilitation and operation management continues until step 14.

Approach and View of systems: Leveraging both top-down and bottom-up approaches concurrently ensures more accurate traceability of requirements between system and component levels, as well as direct and robust linking of the subsystems and components to the overall system architecture. Following this conceptualization, both methodologies allow megaproject participants to manage risks on an individual and collective basis. SI does this through a clear, concise, and robust definition of requirements and constraints, whilst BIM processes follow the requirements in order to design subsystems and components. Despite this alignment, requirements management is being treated as a separate process from BIM.

SI allows traceability of changes and design decisions. Every decision of the megaproject actor affects the requirements and must be validated with appropriate evidence to ensure the satisfaction of the requirements. Failure to satisfy the system requirements or early identification of a potential noncompliance to a requirement identifies a risk to the system and forces risk assessments, which can then be documented against the requirement. Risk assessments and the associated evidence are captured against the requirements in the V&V forms (often matrices known as a VVM), depending on the organization practices. Essentially, organizations capture evidence of compliance with a requirement. This process is considered a weakness of BIM processes, since the BIM technologies have not evolved to allow traceability, unless specific applications are developed in-house. A top-down approach of SI dictates a detailed system definition, which cascades down to the subsystem and component level. BIM then allows subsystem and component design with the use of digital information models.

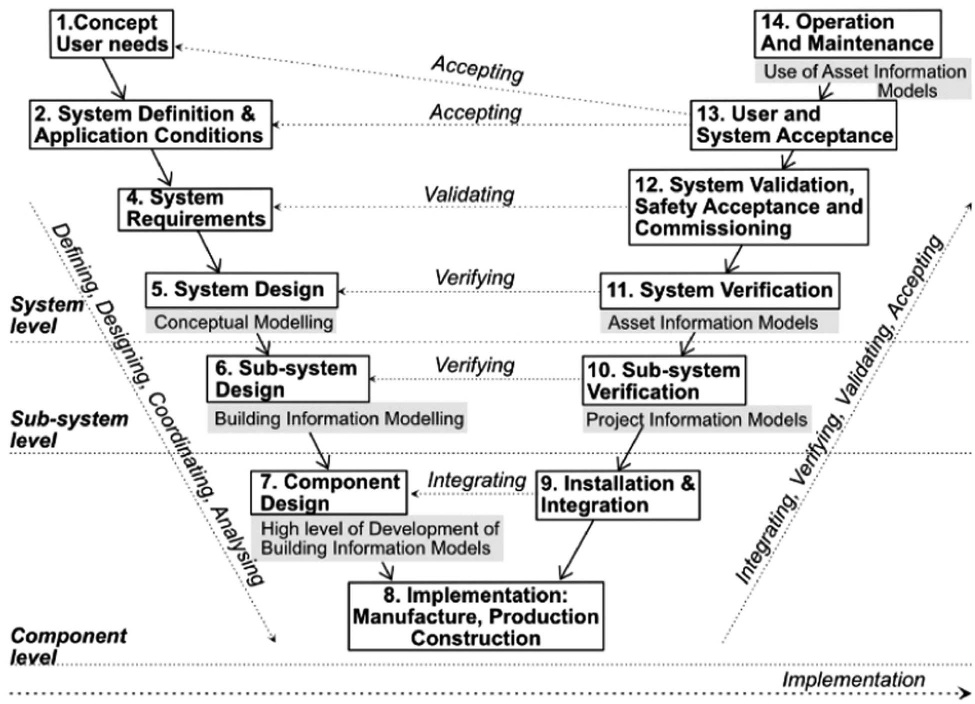

Fig. 1. Integrative V-Model of SI and BIM.

Emergent properties: A system behavior is an emergent property from a SI perspective, whereas in BIM the emergent behavior can only be identified at a subsystem level. SI's strength is a holistic systems approach while, as we concluded, BIM's strength is within the subsystem design and delivery. SI can comprehensively aid the integration processes necessary for BIM implementation in megaprojects with system and subsystem views.

Interfaces: Interface is a central concept in SI. Interfaces are the bridges between disparate entities that are necessary for integration and innovation by specialized teams. Interfaces allow the organization and integration of subsystems and their components into a system [41]. In SI, interfaces can be anything and between anything [7], as SI models are abstractions of an "observer's view" of the system [41]. For example, interfaces can depict the interactions of different contracts, standards, design elements, functions, capabilities, or even combinations of these, such as design elements delivered by different contracts and influenced by a range of standards. Contrary to SI, BIM interfaces are tightly controlled and focused on the interactions of structural and geospatial components; they are typically implemented to standards [e.g., the Industry Foundation Classes (IFC) [42]] to facilitate interoperability [43] of the information across BIM technologies and coordination between specialized teams.

End-users: An important element in SI is the end-user. SI seeks to ensure that the human component of a system enhances the system's effectiveness through human-centered design and the identification of relevant requirements in the system design. This is not a priority consideration for BIM designing, and so it is seen by us as a weakness that can be improved through the use of related SI tools (e.g., the functional block diagrams).

Requirements management and Design: SI is a matter of front-end management of projects and generates critical information for the entire project and system lifecycle, whereas BIM implements and delivers the required information models. In SI, design is implicit, as SI engineers work with abstractions of physical components before commencing engineering designs, hence the importance of requirements identification and management. On the other hand, BIM is founded on explicit designs that result in as-modelled and as-built information. Thus, SI enables better design with the use of BIM, while BIM supports SI's management of the requirements throughout the lifecycle of the project.

Governance: Governance, as shown in Table II, encompasses *Coordination*, *Capabilities*, *Governing body*, *Value process,* and *Core activities*. BIM is usually led by one organization and its use depends on the firm's capabilities with the client organization's capabilities being critical. An implicit consideration in the previous statement is that an organization employs competent staff for BIM use. While systems integrators are key actors in SI, BIM managers are key actors in BIM processes. For this reason, in megaprojects, the governing body is the Systems Integrator, while the BIM manager sits at a lower level of governance within the design organization following the Systems Integrator's lead. A System Integrator holds a very important role as it can break silos inherent in projects that can be translated into BIM processes. Interestingly, the role of system integrators was introduced in construction literature and practice already in 1998 [44]. Recently, the literature has continued discussing the role of architects and general contractors as system integrators in relation to digitalization and BIM specifically [15]. However, system integrators in SI and BIM processes are understood differently. System integrators' roles in BIM projects are typically identified in general contracts to ensure BIM deliverables are delivered as required. While their role is evolving, system integrators in the SI field often take the role of "project steward" that is providing the "guiding mind" and "steadying hand" across all aspects and disciplines to ensure cohesion and the associated outturn benefits in terms of value creation processes.

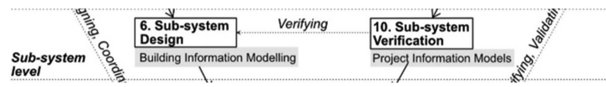

Fig. 2. Critical stage where Crossrail could have prevented signaling integration issues.

D. SI and BIM Complementarity: A Case Study

To illustrate how SI and BIM are complementary in the management of megaprojects, the Crossrail case is presented. Crossrail is one of the most complex underground railways that opened in London in 2022 [45]. It is highly complex from a technical and organizational perspective. Its complexity emerges from the scale of the megaproject, unanticipated interactions [46], as well as the diversity of interdependencies of activities and disciplines [47]. Although Crossrail has implemented both SI and BIM, the literature has documented their implementation separately.

Crossrail has started with BIM implementation. SI was not taken into consideration initially. Considering the risks associated with increased complexity, Crossrail established the first BS1192:2007 compliant common data environment (CDE), a centralized shared repository for managing, sharing, and disseminating design information between disciplinary teams [48]. In Crossrail, CDE supported the production of an integrated design along with the coordination processes that enabled the supply chain to coordinate their designs. Crossrail met the U.K. government's BIM Level 2 targets [49] for collaborative working, the use of building information models in coordination, and sharing standardized file formats through CDE. However, the implementation of BIM in Crossrail was challenged by organizational behaviors more than technical ones [50]. For this reason, Crossrail chose to encourage rather than mandate the use of BIM. BIM implementation across the project was documented as sporadic and limited [48]. A lack of clear protocols to govern the use and ownership of building information models hindered the ability to build trust and foster collaboration between disciplinary teams [48]. A lack of a BIM execution plan that outlines roles, responsibilities, authorities, ownership, and alignment with the requirements led to poor clarity of BIM deliverables from the contractors.

To address the behavioral and organizational challenges, Crossrail decided to adopt a lifecycle approach to information management, while extending the use of BIM into construction processes, which further illuminated difficulties for BIM implementation. Most of the construction contracts were already awarded and partly executed, making the implementation of changes difficult to justify. Crossrail sought to apply a light-touch approach to construction management with BIM because contractors had full responsibility for their own detailed design and construction works [48]. Subsequently, this resulted in a varied application of BIM practices by the contractors throughout the procurement, fabrication, and construction phases.

One of the serious implications of the inconsistent approach among contractors was the challenge of integrating multiple complex signaling systems (communications-based train control and European rail traffic management system), which significantly delayed the opening of Crossrail [3]. This event initiated a discussion about the relationship between BIM and integration [51]. The early challenges associated with the use of digitally created information with BIM processes have illuminated a need for stronger integration between teams. At the end of the megaproject lifecycle, Crossrail adopted an SI approach [52]. For Crossrail successful, though delayed, the SI approach meant delivering a railway that is safe, operable, maintainable, and performs to the required levels of capability [53].

In the case of Crossrail, timing was important. It was only in the later stages of the delivery that it became apparent that the project was poorly equipped to address an uncertain and changeable lifecycle. Interface points had to be redefined to address the introduction of cyber-technological systems and interdependent interactions that were not adequately understood until then [52]. Typically, interdependencies transverse and interfaces evolve throughout the project lifecycle, from design to handover. This progressive and dynamic behavior of interfaces requires a lifecycle approach, like the one depicted in Fig. 1, in order to monitor, trace, anticipate, control, and treat undesirable developments.

Our empirical observation of Crossrail's disintegrated signaling system supports our argument that SI's role is to guide and enable BIM processes for early detection [43] and resolution of subsystem misalignments and system deviations. Fig. 2 (snippet of Fig. 1) depicts the critical stage where an early adoption of SI and subsequent synthesis of SI and BIM results could have helped SI and BIM specialists (i.e., *Actors*, Table I) to anticipate and prevent the later integration issues of the signaling systems. SI should be client led, commencing at the inception (i.e., Stage 1, *Concept*, Fig. 1) of a project and then continuing throughout the project lifecycle (i.e., Stages 2-14, Fig. 1). Despite its late adoption, SI has proved critical in providing clarity and focus on the key steps to getting the railway into passenger service in 2022 [53]. The SI team also provided the environment for the training and signaling contacts to collaborate and resolve issues together.

SI is used to manage information and interdependencies across the product lifecycle. It requires an integrated organization structure that addresses multiple interfaces between systems needed for BIM implementation for value realization [53]. The lack of uniform and integrated approaches to delivering megaprojects, as evidenced in the Crossrail case, is likely to cause major delays. Numerous examples exist in Crossrail where parties from both sides of an interface met their contractual requirements and everything was compliant to specification, only to find that the interface did not work in practice to deliver a fully functional or reliable end-to-end system [53].

Despite that the existing literature does not make an explicit reference to a combination of SI and BIM in Crossrail, our overriding observation and practical experience on Crossrail has demonstrated that, eventually, this combination contributed to the project's stability and cohesion. The usage of integrated and collaborative processes enabled by web services and compliant with emerging IFC standards [54]—a standardized, digital description of the built asset industry—is a testament to that.

SI and BIM's simultaneous integration at a system level from the start was necessary and could have supported risk management and reduction of defects. Defects found early means they are dealt with at the system level and by finding defects early, the resolutions can be put in place before significant manufacturing or advanced development has been undertaken. This approach outweighs waiting for "finished" individual systems before testing them together [48], unlike what happened with the unsuccessful integration of the four signaling systems of Crossrail. A key enabler in achieving this goal is using SI to guide BIM processes throughout the megaproject lifecycle to develop a culture of shared responsibility, collaboration, and accountability between the teams while ensuring subsystems and components are compliant with requirements. SI is compatible with BIM because it allows integration at not just technical but also organizational levels, seeking out opportunities for early analysis of the system functioning and operating. As digital information has become a megaproject deliverable [10], [47], BIM processes have changed supply chain interactions and relationships with owners, operators, and end-users. SI plays an important role in guiding the integration of those deliverables.

The Crossrail case demonstrated clearly that SI and BIM are not only compatible and complementary for the management of megaprojects, but also reinforce value creation throughout the lifecycle of system of interest development and delivery.

IV. Discussion and Conclusion

The contribution of this work to the existing literature is twofold. First, we proposed that SI and BIM methodologies reinforce each other and can serve the management of megaprojects effectively if implemented concurrently. While conceptualizing SI and BIM complementarity and compatibility, we articulated microfoundations of SI and BIM that can reinforce each other. We identified that what may be a weakness for the one could be a strength for the other one. We argued that SI and BIM should be implemented concurrently to strengthen the management of information, quality, and efficiency, and not just as a "nice to have approach." SI complements BIM in terms of systems theory, interfaces, systems language, and requirements management of information throughout the lifecycle of the system of interest. We considered the microfoundations of both methodologies in terms of their theoretical and practical complementarity by illustrating the case study of Crossrail.

Second, by conceptualizing their complementarity and compatibility, we combined the two methodologies into one framework and model. We extended the existing literature [3], [9] towards a more granular and nuanced view of SI and BIM. Our analysis indicates that although SI and BIM have evolved separately, their theoretical underpinnings and microfoundations have compatible and complementary relationships that can aid the management of megaproject complexities. Our framework tackles integration from an information management perspective. It focuses on the integrated management of megaprojects, rather than on supply chain integration. We believe our study is one of the first to conceptualize the complementarity and compatibility of SI and BIM in the infrastructure sector.

The proposed framework (see Table II) and the accompanying integrative model (see Fig. 1) combine the SI and BIM methodologies for the management of megaprojects. SI guides and enables BIM processes, it tackles the system level, whereas BIM tackles subsystems and components. Our unified framework is a theoretical foundation for future research on the management of megaprojects to tackle emerging complexities. It is worth noting that the proposed framework is not intended to replace existing approaches to megaproject management. Rather, the ultimate aim is to better align and integrate existing practices, which so far have been evolving separately.

Considering that this article is only the first step towards integrating the two methodologies, the proposed framework needs further theoretical and empirical development and consolidation. Furthermore, there is a need to advance our understanding of how SI enables, guides, and reinforces BIM processes to deliver digital information for the management of infrastructure assets. Although we have presented key microfoundations, granularity and refinement could be done at a deeper level, by specifically indicating the potential interdependencies of those microfoundations at organizational and technical levels. This article has not made any attempt to discuss the project management aspects, instead, emphasis was placed on the technical and technological aspects of SI and BIM. Future research could investigate the implications of SI and BIM on the organizations participating in megaprojects.

Our theory-building approach was based on an analytical approach to the literature review supported by our own industry experience in infrastructure megaprojects. Therefore, this work requires further empirical investigation and validation. For example, there are ongoing megaprojects that implement SI and BIM such as U.K.'s high-speed railway (HS2) [55], but not necessarily in an integrated manner. Thus, we call for studies that are longitudinal and empirical in nature to investigate the theory-practice alignment, strengths, and weaknesses of the proposed framework within the existing case of HS2. There are a number of questions to be posed. For example: How were SI and BIM implemented in megaprojects? What interactions between the microfoundations of SI and BIM have produced success and contributed to failure? We further believe that a joint SI and BIM implementation is context dependent, with culture (of country and sector), local standards and laws, local economic conditions, technology trust and development, and other individual approaches influencing their implementation. These should be also studied. A list of limitations and benefits specifically about BIM can be found in [56]. Other relevant works include [57] and [58].

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References

[1] B. Flyvbjerg, "What you should know about megaprojects and why: An overview," *Project Manage. J.*, vol. 45, no. 2, pp. 6–19, 2014.
[2] E. Gholz, A. D. James, and T. H. Speller, "The second face of systems integration: An empirical analysis of supply chains to complex product systems," *Res. Policy*, vol. 47, no. 8, pp. 1478–1494, 2018.
[3] J. Whyte and A. Davies, "Reframing systems integration: A process perspective on projects," *Project Manage. J.*, vol. 52, no. 3, pp. 237–249, 2021.
[4] J. Zhu and A. Mostafavi, "Performance assessment in complex engineering projects using a system-of-systems framework," *IEEE Syst. J.*, vol. 12, no. 1, pp. 262–273, Mar. 2018.
[5] I. G. Vargas and R. T. V. Braga, "Understanding system of systems management: A systematic review and key concepts," *IEEE Syst. J.*, vol. 16, no. 1, pp. 510–519, Mar. 2021.
[6] G. Locatelli, M. Mancini, and E. Romano, "Systems engineering to improve the governance in complex project environments," *Int. J. Project Manage.*, vol. 32, no. 8, pp. 1395–1410, 2014.
[7] SEBoK Editorial Board, *Guide to the Systems Engineering Body of Knowledge (SEBoK)*, version 2.4. Hoboken, NJ, USA: Trustees Stevens Inst. Technol., 2021.
[8] C. M. Eastman, "*BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. Hoboken, NJ, USA: Wiley, 2011.
[9] R. Sacks, C. Eastman, G. Lee, and P. Teicholz, "*BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*. Hoboken, NJ, USA: Wiley, 2018.
[10] J. Whyte, "How digital information transforms project delivery models," *Project Manage. J.*, vol. 50, no. 2, pp. 177–194, 2019.
[11] M. A. Bone, M. R. Blackburn, D. H. Rhodes, D. N. Cohen, and J. A. Guerrero, "Transforming systems engineering through digital engineering," *J. Defense Model. Simul.*, vol. 16, no. 4, pp. 339–355, 2019.
[12] Y. Chen and J. Jupp, "BIM and through-life information management: A systems engineering perspective," in *Proc. Adv. Inf. Comput. Civil Construction Eng., IT Des., Construction, Manage.*, 2019, pp. 137–146.
[13] J. Whyte et al., "A research agenda on systems approaches to infrastructure," *Civil Eng. Environ. Syst.*, vol. 37, no. 4, pp. 214–233, 2020.
[14] ICE, "A systems approach to infrastructure delivery," A review of how systems thinking can be used to improve the delivery of complex infrastructure projects, 2020. [Online]. Available: https://myice.ice.org.uk/getattachment/knowledge-and-resources/briefing-sheet/a-systems-approach-to-infrastructure-delivery/ICE_Systems_Report_final.pdf.aspx
[15] A. Davies and I. Mackenzie, "Project complexity and systems integration: Constructing the London 2012 Olympics and Paralympics Games," *Int. J. Project Manage.*, vol. 32, no. 5, pp. 773–790, 2014.
[16] J. O. Grady, "*System Integration*, vol. 5. Boca Raton, FL, USA: CRC Press, 1994.
[17] A. Davies, D. Gann, and T. Douglas, "Innovation in megaprojects: Systems integration at London Heathrow Terminal 5," *California Manage. Rev.*, vol. 51, no. 2, pp. 101–125, 2009.
[18] K. B. Hass and K. B. H. PMP, "*Managing Complex Projects: A New Model*. Oakland, NY, USA: Berrett-Koehler Publishers, 2008.
[19] N. Naderpajouh, "Interactional analysis of emergent risks in institutionally diverse construction projects," Ph.D. Dissertation, Purdue Univ., 2013.
[20] M. Hobday, A. Davies, and A. Prencipe, "Systems integration: A core capability of the modern corporation," *Ind. Corporate Change*, vol. 14, no. 6, pp. 1109–1143, 2005.
[21] K. Remington and J. Pollack, "*Tools For Complex Projects*. Aldershot, U.K.: Gower Publishing, 2007.
[22] J. Whyte, A. Stasis, and C. Lindkvist, "Managing change in the delivery of complex projects: Configuration management, asset information and 'Big Data'," *Int. J. Project Manage.*, vol. 34, no. 2, pp. 339–351, 2016.
[23] S. D. Eppinger and T. R. Browning, *Design Structure Matrix Methods and Applications*. Cambridge, MA, USA: MIT Press, 2012.
[24] C. E. Dickerson and D. Mavris, "A brief history of models and model based systems engineering and the case for relational orientation," *IEEE Syst. J.*, vol. 7, no. 4, pp. 581–592, Dec. 2013.
[25] S. Purohit and A. M. Madni, "A model-based systems architecting and integration approach using interlevel and intralevel dependency matrix," *IEEE Syst. J.*, vol. 16, no. 1, pp. 747–754, Mar. 2022.
[26] J. Holt, S. Perry, R. Payne, J. Bryans, S. Hallerstede, and F. O. Hansen, "A model-based approach for requirements engineering for systems of systems," *IEEE Syst. J.*, vol. 9, no. 1, pp. 252–262, Mar. 2014.
[27] J. A. Estefan, "Survey of model-based systems engineering (MBSE) methodologies," *Incose MBSE Focus Group*, vol. 25, no. 8, pp. 1–12, 2007.
[28] J. Towers, "Update on MBSE & BIM work-stream," INCOSE U.K. MBSE Interest Group, 2017. [Online]. Available: http://www.incosewiki.info/Model_Based_Systems_Engineering/Files/1/16/MBSE_v_BIM_Presentation_26-09-17.pdf
[29] C. Eastman, "The use of computers instead of drawings in building design," *AIA J.*, vol. 63, no. 3, pp. 46–50, 1975.
[30] S. M. Latham, "Constructing the team," HMSO Pub., 1994.
[31] A. Wolstenholme et al., "Never waste a good crisis: A review of progress since rethinking construction and thoughts for our future," Constructing Excellence, Loughborough Univ., 2009.
[32] A. Kiviniemi, "The effects of integrated BIM in processes and business models," in *Distributed Intelligence in Design*, T. Kocaturk and B. Medjdoub, Eds. Chichester, UK: Wiley Blackwell, 2011, pp. 125–135.
[33] International Organization for Standardization, "Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 1: Concepts and principles," ISO 19650-1:2018(en), 2019. [Online]. Available: https://www.iso.org/obp/ui/en/#iso:std:68078:en
[34] R. Howard and B. C. Björk, "Building information modelling–Experts' views on standardisation and industry deployment," *Adv. Eng. Informat.*, vol. 22, no. 2, pp. 271–280, 2008.
[35] J. Underwood et al., "Transforming the productivity of people in the built environment: Emergence of a digital competency management ecosystem," in *Handbook of Research on Driving Transformational Change in the Digital Built Environment*. Hershey, PA, USA: IGI Global, 2021, pp. 430–466.
[36] T. Kocaturk and A. Kiviniemi, "Challenges of integrating BIM in architectural education," in *Proc. eCAADe Conf*, The Netherlands, 2013.
[37] S. Vass and T. K. Gustavsson, "Challenges when implementing BIM for industry change," *Construction Manage. Econ.*, vol. 35, no. 10, pp. 597–610, 2017.
[38] R. Katila, R. E. Levitt, and D. Sheffer, "Systemic innovation of complex one-off products: The case of green buildings," in *Organization Design*. Bingley, U.K.: Emerald Publishing Limited, vol. 40, 2018, pp. 299–328.
[39] A. Prencipe, A. Davies, and M. Hobday Eds., *The Business of Systems Integration*. Oxford, U.K.: OUP, 2003.
[40] T. R. Gruber, "A translation approach to portable ontology specifications," *Knowl. Acquisition*, vol. 5, no. 2, pp. 199–220, 1993.
[41] A. Kossiakoff, S. M. Biemer, S. J. Seymour, and D. A. Flanigan, "*Systems Engineering Principles and Practice*. Hoboken, NJ, USA: Wiley, 2020.
[42] *Systems and Software Engineering—System Life Cycle Processes*, ISO/IEC/IEEE 15288, 2015.
[43] E. Brusa, "Digital twin: Toward the integration between system design and rams assessment through the model-based systems engineering," *IEEE Syst. J.*, vol. 15, no. 3, pp. 3549–3560, Sep. 2021.
[44] G. Winch, "Zephyrs of creative destruction: Understanding the management of innovation in construction," *Building Res. Inf.*, vol. 26, no. 5, pp. 268–279, 1998.
[45] BBC, "Elizabeth line grand opening: As it happened [Press release]," 2022. [Online]. Available: https://www.bbc.com/news/live/uk-england-london-61507125/page/4
[46] M. Efatmaneshnik and H. A. Handley, "Task complexity measurement framework for human systems integration," *IEEE Syst. J.*, vol. 15, no. 2, pp. 2787–2797, Jun. 2021.
[47] M. Taylor, "Crossrail project: Building a virtual version of London's Elizabeth line," in *Proc. Inst. Civil Engineers-Civil Eng.*, 2017, vol. 170, no. 6, pp. 56–63.
[48] S. Smith, "Building information modelling–moving Crossrail, U.K., forward," *Proc. Inst. Civil Engineers-Manage., Procurement Law*, vol. 167, no. 3, pp. 141–151, 2014.
[49] HM Government, 2012, "Building information modelling," Industrial strategy: government and industry in partnership. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/34710/12-1327-building-information-modelling.pdf

[50] D. Tyner, "Crossrail Systems Integration–Lessons learned and good practice in managing interdisciplinary systems integration through each stage of the Crossrail Programme," in *Crossrail Project: Infrastructure Design and Construction*, 2022, pp. 137–144, London, U.K.: ICE Publishing.

[51] S. N. Pollalis and D. Lappas, "Crossrail -Elizabeth Line 1," 2019, [Online]. Available: https://research.gsd.harvard.edu/zofnass/files/2019/04/20190327_Crossrail-case-study.pdf

[52] K. Muruganandan, A. Davies, J. Denicol, and J. Whyte, "The dynamics of systems integration: Balancing stability and change on London's Crossrail project," *Int. J. Project Manage.*, vol. 40, no. 6, pp. 608–623, 2022.

[53] N. McCrimmon, T. Afolabi, and M. Thomas, "Crossrail Systems Integration–Lessons learned and good practice in managing interdisciplinary systems integration through each stage of the Crossrail Programme," in *Crossrail Project: Infrastructure Design and Construction*. London, U.K.: ICE Publishing, 2022, pp. 137–144.

[54] Crossrail Ltd., "Crossrail BIM principles," 2017. [Online]. Available: https://ll.crossrail.co.uk/documents/crossrail-bim-principles/

[55] HS2, "Digital Engineering and BIM," 2022, [Online]. Available: https://www.hs2.org.uk/building-hs2/innovation/digital-engineering-and-bim/

[56] M. Chatzimichailidou and Y. Ma, "Using BIM in the safety risk management of modular construction," *Saf. Sci.*, vol. 154, 2022, Art. no. 105852.

[57] D. Migilinskas, V. Popov, V. Juocevicius, and L. Ustinovichius, "The benefits, obstacles and problems of practical BIM implementation," *Procedia Eng.*, vol. 57, pp. 767–774, 2013.

[58] D. Bryde, M. Broquetas, and J. M. Volm, "The project benefits of building information modelling (BIM)," *Int. J. Project Manage.*, vol. 31, no. 7, pp. 971–980, 2013.

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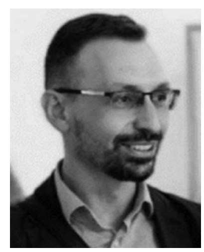

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