17 BIM and Through-Life Information Management: A Systems Engineering Perspective

Yu Chen and Julie Jupp

Abstract

The digital era of construction has enabled new types of decision support for all phases of the building lifecycle. New capabilities to support the management of end-to-end service operations are emerging due to the outputs of building information modelling. Previous research has identified how the application of systems engineering activities in construction can inform the development of new methods and processes to better support a facility's life cycle. However, gaps remain in holistic systems approaches relative to how data is structured, reused and managed through-life. The paper discusses systems engineering management activities and reviews the related literature, examining the significance of these concepts in different sectors of construction. The paper identifies gaps in collaborative and progressive modelling methodologies and identifies the main challenges that industry face in adopting a systems mindset when implementing BIM on complex projects.

Keywords

Building information modelling • Information management • Lifecycle • Systems engineering • Integration

17.1 Introduction

Within the life cycle of a building asset, different groups of actors are involved in the generation and sharing of data and information throughout the design, construction and operations and maintenance (O&M) phases [1]. The fragmented nature of both the construction and facilities management (FM) industries leads to the inefficient exchange and low reuse of building asset information [1, 2]. During the past decade with the rise in computing power, more effective utilization of building asset information has improved globally [3]. Building Information Modelling (BIM) is widely regarded as the foundation of the fourth industrial revolution [3]; BIM is defined as "a new approach to design, construction, and facilities management, in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in digital format" [4]. The implementation of BIM in design and construction phases brings with it evident benefits in terms of cost and schedule control [5], which are quite marginal in perspective of the gains to be made in the O&M of an asset's service life [6]. Many issues relate to the management of the flow of digital building information [7]; where for example, problems manifest in the management of the vast amounts of data and information generated during design and construction phases, some of which is not valuable to the operational phase of the asset [8].

To capitalize fully on the potential of BIM to help optimize the flow of digital information and process activities, it is necessary to define a structuring concept linking BIM models, BIM uses, related information flows in the project together, with workflows linked with user profile information [9, 10]. Previous researchers have identified how the application of

Y. Chen · J. Jupp (✉)
School of Built Environment, University of Technology Sydney, Sydney, Australia
e-mail: Julie.Jupp@uts.edu.au

Y. Chen
e-mail: Yu.Chen@uts.edu.au

I. Mutis and T. Hartmann (eds.), *Advances in Informatics and Computing in Civil and Construction Engineering*,
https://doi.org/10.1007/978-3-030-00220-6_17

systems engineering (SE) activities in construction have significant potential to structure the flow of data and information as well as process activities [11, 12], "where integration is important to ensure that parts, components, units, subassemblies, subsystems and systems work together as a whole" [13], and are able to serve different business processes across the organization. SE is a multidiscipline approach and means to enable the realization of successful systems in complex environments [14]. It emphasizes the importance of the traceability of the requirements of end users, operators, maintainers, suppliers, etc. However, whilst SE provides a robust set of methods (e.g., information requirements management [3], configuration management [15, 16] and change management [17, 18]), gaps remain in how these methods translate to the complex nature of construction projects, where challenges surround the way data is structured, verified, reused and managed over the life cycle of a building asset [1, 3, 19, 20]. Recent initiatives to develop BIM Standards (e.g., PAS 1192 and ISO/DIS 19650) have sought to address these issues. However, an understanding of how SE methods and processes can be used to implement collaborative methodologies beyond these high-level guidelines is currently lacking.

Against this backcloth, this paper presents a literature review of those BIM related initiatives in recent construction domain research aimed at overcoming the gaps in collaborative progressive modelling methodologies and the challenges of information management throughout the building asset lifecycle. The paper introduces systems engineering management activities and enablers before reviewing related literature and discussing the relevance of these concepts to the application of BIM in construction. The paper then identifies specific gaps in model progression methodologies and reveals where the challenges lie for the industry in developing a systems mindset to the implementation of BIM on complex projects.

17.2 Background

With increasing uptake of digital construction technologies, a greater understanding of the through-life information management capabilities relative to the required backbone infrastructure, data structures, cloud provisioning services, and enterprise architectures are beginning to grow. A major challenge for both the physical and digital asset life cycle is "the existence of various data format standards, few practice standards and no lifecycle information standards" [21]. Although efforts have been made to ensure the data standards from various domains are interoperable, it is still difficult to determine "what data and context are required for each phase of the product lifecycle" [21].

Over the last three decades, the complex, discrete manufacturing industries, such as aerospace and shipbuilding, have made significant progress in productivity increases and management efficiencies. This is in large part due to a more seamless integration of systems enabled by SE capabilities and Product Lifecycle Management (PLM) platforms [9, 21, 22]. This improvement, however, has not been achieved in the design, delivery and operations of building assets [9]. Given the increasingly cyber-physical and digital nature of the construction and FM industries in the last decade, it is expected that the SE approaches developed in other sectors have significant potential to inform approaches to information integration across the building asset's life cycle [9, 11, 13].

In the past decade, the adoption of SE in the construction industry has gained an increasing interest both in practice and in academia [1, 13, 23–25]. In practice, organizations in civil engineering have long realized the value of SE methods in terms of making projects manageable and better suited to customer requirements [23]. The International Council on Systems Engineering (INCOSE) Infrastructure Working Group, for example, is exploring the use of SE in civil engineering. Also in the Netherlands, ProRail [23] published the third version of a general SE guideline for civil engineering that addresses three levels—sector, organizational, and project—targeting different user groups based on the experience gained through the application of SE methods.

Some notable previous research works have been dedicated to the study of adopting SE approaches in construction projects [1, 13, 24, 25]. Whyte [13] provides a comprehensive review of system integration research in the delivery and operation of infrastructure and suggest future directions for research on systems integration within civil infrastructure. Whyte [13] highlights the potential of combining "data-sets and model-based systems engineering, BIM and performance-based models" and using "new forms of data analytics to reveal new patterns" [13]. A chief concern that raised by the translation of SE in the built environment is the reliance on a single source of data and the potential for errors and significant failures in the absence of robust processes for data verification and validation throughout the project life cycle [13]. Hoeber and Alsem [1] presented a way of working that utilizes open-standard BIM, SE ontologies, object libraries and an Information Delivery Manual to support information management throughout the life cycle of infrastructures assets. However, further evaluation and extension case studies are needed to measure the benefits of the approach in a quantitate way. Mata et al. [24] developed a Systems of Systems model along the SE concepts and Systems Modeling Language (SysML) to evaluate the sustainability performance of infrastructure projects. De Graaf et al. [25, 26] assessed the level of SE applications in six construction projects of the Dutch Water Board based on the SE process model developed by the U.S. Department of Defense (DoD). This growing body of literature signals the case for understanding SE methods relative to the unique context and requirements of designing, delivering and operating complex building assets.

Although the application of SE approaches in complex horizontal infrastructures (e.g., rail projects) has been explored during the last decade, there are few documented cases of the use of SE methodology in the complex vertical building sectors (e.g. smart/intelligent building, hospital). The main barriers lie on the unique industry structure and supply chain [2, 9]. Taking the aerospace industry as an example, the industry's structure is globalized and consolidated, with only a few large firms dominating the industry [2, 9]. Conversely, the construction industry is a localized and highly fragmented industry, with many small firms permeating the industry, make through-life information management challenging during the delivery phases of complex building projects [2, 9].

17.3 Systems Engineering Management Activities and Enablers

The most common and accepted definition of SE was proposed by INCOSE: "SE is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirement, and then proceeding with design synthesis and system validation while considering the complete problem." [14]. Systems Engineering Management (SEM), as a branch of SE, is the application of scientific, engineering, and managerial efforts to address *operational needs and client requirements*, to transform said need into system configuration and performance parameters, and to integrate related technical parameters and managerial factors to meet performance objectives [15]. SEM processes and toolsets are therefore essential to supporting SE implementations and achieving its benefits [27].

In the past decade, construction industry initiatives are increasing efforts to develop model-based information management methods. For example, in preparation for the BIM Mandate in 2016 in the UK, the British Standard Institute published the PAS[1] 1192-2: 2013 and later PAS 1192-3: 2014. PAS 1192-2 specifies an "information management process to support BIM Level 2 in the capital/delivery phase of projects" [28]. In contrast, PAS 1192-3 focuses on "the operational phase of assets irrespective of whether these were commissioned through major works, acquired through transfer of ownership or already existed in an asset portfolio" [29]. Both Standards introduce new concepts and system-based processes to BIM implementation.

The following section discusses the role of SE in BIM deployment and examines the SEM activities and enablers that have the potential to establish a systems-based approach to more effective management of building information throughout the life of an asset. Accordingly, equivalent BIM initiatives in the construction industry are compared with SE methods to highlight significant gaps in BIM methodology.

17.3.1 Systems Engineering Management Activities

According to the DoD [30], SEM is achieved via the integration of three activities: (1) development phasing, (2) life cycle integration, and (3) systems engineering process.

Development phasing. Development phasing aims to control the design process and define design baselines that govern each level of development [30]. The SE process is applicable at each level (or phase) of system development, one level at a time, to produce the corresponding requirement descriptions of each level, known as "configuration baselines" [30]. Thus, configuration management (CM) under an SE approach involves five distinct activities: CM Planning and Management, Configuration Identification, Configuration Control, Configuration Status Accounting, and Configuration Verification and Auditing [31]. During system decomposition and definition, requirements, functions, and objects (R/F/O) are verified with higher-level R/F/O before then being validated against client expectations [32]. The components of a system are then integrated and recomposed into the product. System components are therefore verified with corresponding R/F/O at each level with ongoing validation [27, 32]. Verification and validation (V&V) are not treated as separate phases but are integrated activities executed continuously throughout the SE process [32].

[1]Publicly Available Specification.

In a BIM-enabled construction context, to date there has been no equivalent structured approach to CM developed as a way to systematically managing system decomposition and definition, requirements, functions, and objects; nor as a way to manage change throughout the asset lifecycle in order to maintain building system integrity. The main challenges of implementing CM in construction surround difficulties in structuring and coordinating the execution CM activities across the project enterprise and in accordance with the building system hierarchy. In terms of V&V, there are reasonable levels of maturity in model auditing, design coordination, and associated quality assurance processes across the detailed design and construction documentation phases. However, the preparation of a holistic approach to a V&V plan in early project stages is often overlooked [26].

Life cycle integration. Life cycle integration involves the customer and stakeholders in the design process, ensuring that the design is viable and aligns with the customer's requirement throughout the life of the system or asset [30]. It requires the early involvement of all stakeholders to identify and document their needs and requirements which is also known as project planning [30]. In subsequent stages, the project must be monitored and controlled carefully to ensure alignment with stakeholders requirements [22].

Similar defined processes can be identified in the construction industry. To meet the challenge of defining *what information* is required, *from whom* and at *what level of detail* several industry specifications have addressed the definition of modelled objects and information embedded within them at the project preparation and brief phase [33], with examples of BIM guidelines and execution templates common in most countries. These guidelines and templates are normally targeted at supporting the development of the BIM execution plan (BEP), also known as a BIM management plan (BMP) [34]. Within these plans, the model element table (MET) is designed to identify information requirements of the project at an early stage [34]. It summarizes the list of model elements but also "indicates the level of development (LOD) to which each model element author (MEA) is required to develop model element content before the conclusion of each phase" [35]. The BIM model is then developed according to the requirements defined in the MET [34]. To support this process, progressive model development methodologies and protocols [34], such as UK's PAS1192-2 [28], Canada's AEC protocol [36] and the USA's LOD specification [37] have been developed.

Systems Engineering Process. The specification of the Systems Engineering Process, or SEP, lies at the heart of all SEM activities. It aims to provide a structured but flexible process that "transforms needs and requirements into a set of system product and process descriptions, generate information for project decision-makers, and provide input for the next level of development" [30]. Based on the SEM model by the U.S. DoD [30], de Graaf et al. [26] propose a SEP framework to analyze the implementation of SE in an engineering consulting firm in the civil engineering sector. The engineering consulting firm studied recognized the significance of SE in relation to their daily practices, and in 2010 made the decision to implement SE in its business more prominently to professionalize and improve the quality of processes and its products, whilst reducing failure costs [26]. Figure 17.1 shows the ten SE elements implemented by the firm; between "input" and "output" there are three core SE activities—*requirements analysis*, *functional analysis and allocation*, and *design synthesis* —and six feedback elements—*requirement loop, design loop, design verification and validation, specification verification and validation* [25, 26].

Requirements analysis (activity 1) is aimed at translating client needs and demands (process inputs) into specific, measurable, acceptable, realistic, and time-bound requirements [25]. A verification and validation (V&V) plan linking to requirements is normally shaped by the project team [26]. Function analysis and allocation (activity 2) supports the derivation of functions from requirements, composing functional architecture, converting functions into solution free objects, and allocating requirement to functions/objects [26]. In design synthesis (activity 3), several design alternatives are developed based on the "solution neutral" objects and only one of them is selected [25]. During this activity, a key objective is for the decision-making process to be recorded and traceable [25]. Feedback loops and interactions (activities 4–9) between core SE activities ensure the correct linkages among them as well as the continuous updating, checking and documentation of the design so as to maintain consistency with the last iteration's developments and insights [25].

Whilst there are limited case studies of the application of SEP in a civil engineering context, in the wider construction industry there are no documented examples. Whilst not explicitly recognized as a SEP, PAS 1192-3 proposes a model-based information management process map of the asset life cycle (see Fig. 17.2). The process map is comprised of the specification of a Common Data Environment (CDE) based on BS 1192 and ISO/TS 8000 and illustrates the links between the data and information generated using the CDE as the single source of asset information [29]. This process provides a comprehensive overview of data and information flows throughout the asset life cycle. However, it is an information flow instead of an activity-based or task-based description of processes which generate, verify, update, and validate information.

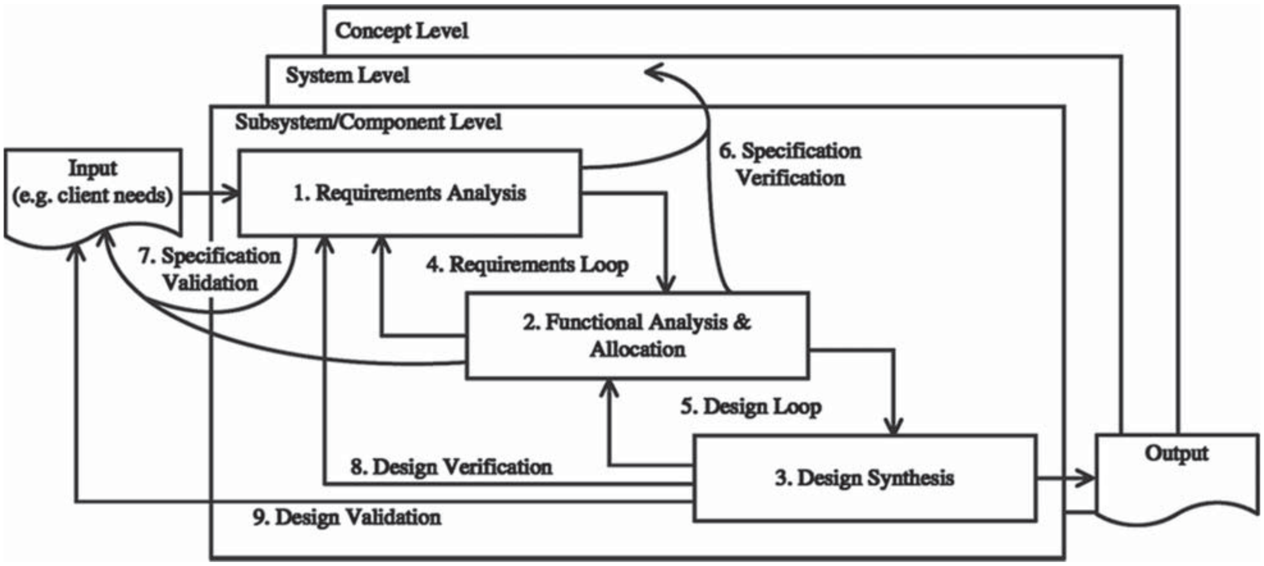

Fig. 17.1 The SEP in the civil engineering industry based on U.S. DoD [25]

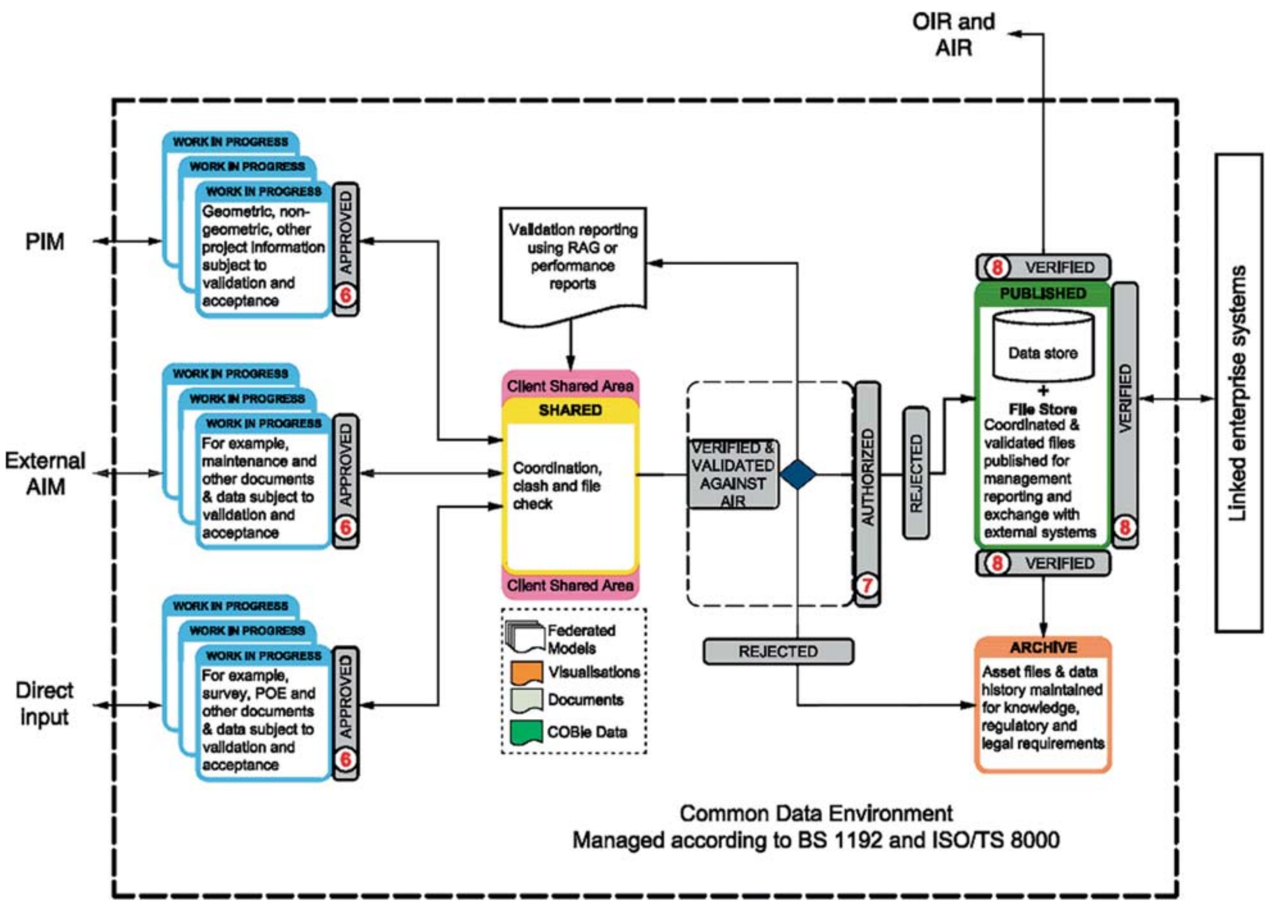

Fig. 17.2 Information process mapping within CDE [29]

17.4 Systems Engineering Management Enablers

To implement SEM activities and realize the benefits of systems thinking, supporting enablers including management and collaboration structures and toolsets have been developed and refined over the years in complex manufacturing sectors. Locatelli et al. [27] identify seven enablers underpinning SEM activities. Here we explore their connection to comparable BIM concepts and initiatives; where gaps are identified we discuss the potential application of SE and SEM activities.

Integrated Product Teams. Achieving life cycle integration requires the simultaneous consideration of all life cycle needs and requirements at the early stage. It has been long known that complex system integration can be greatly enhanced through the early involvement of interdisciplinary teams, also known as integrated product teams (IPTs) [30]. The IPTs normally consist of all stakeholders who will influence project success, such as customers, clients, end-users, contractors, sub-contractors, and suppliers [27].

Similar concepts in construction are represented in frameworks supporting Integrated Project Team (IPT) and Integrated Project Delivery (IPD). The AIA's[2] IPD guideline recognizes the value of an integrated team as the lifeblood of IPD [38]. Similarly, ACIF[3] and APCC[4] in Australia have developed guidelines supporting project team integration [39]. The OGC in the UK has also proposed guidelines for IPT in perspective of team working and partnering [40]. The composition of integrated project team normally consists of all stakeholders.

Systems Integration Process. The purpose of systems integration processes are to achieve the "system-of-interest" by progressively combining system components in alignment with system requirements using an "integration strategy" [14]. Activities include defining an integration strategy, scheduling integration, assembling system elements, validating and verifying information flow across interfaces at each level of assembly, and recording integration information [14]. The continuous engagement of the IPT is essential to realize the potential of any systems integration process, ensuring the improvement of information flows, coordination, situation visibility, rework reductions and the lowering of participant frustration [41].

In a construction context, Davies and Mackenzie [42] explored the implementation of systems integration for the London Olympics. The research-based project was aimed at managing the complexity of multiple large complex projects by decomposing each into different levels of systems integration with clearly-defined interfaces and buffers between levels and subsystems. Davies and Mackenzie identified the most challenging aspects of systems integration as establishing processes to maintain stability while responding dynamically to uncertain and changing conditions [42], a perennial problem common to most large, complex construction projects.

SE Management Plan. The SE Management Plan is the top-level plan for managing the SE effort [14]. The SE Management Plan defines "how the project will be organized, structured, and conducted and how the total engineering process will be controlled to provide a system that meets stakeholder requirements" [14].

In a construction context, a comparable BIM related initiative is the BEP/BMP discussed above in the "Life cycle integration" section. A well-conceived and documented BEP/BMP developed at the early stage of the project with input and buy-in from all stakeholders can structure the total architectural and engineering design as well as the construction process. The BEP/BMP can be used to control how the design and progressive modelling of the facility will be structured across the design and construction phases of project delivery, providing a document that specifies *what information* is needed, *from whom* and at *what level of detail* meets stakeholder requirements. However, the quality and consistency of BEP/BMP vary widely, especially with regards to the specification of workflows, model use, model responsibilities, and model-based information exchange [43].

Requirements Management. Requirements management in SEP involves the capture, analysis, and tracking of system requirements using defined workflows and supporting technologies [27]. Requirements management tools support rigorous documentation and version control, relationships between multiple requirements, and traceability of each requirement [27]. One widely adopted requirement management software is IBM Rational DOORS. As a multi-platform and enterprise-wide tool, it is designed to capture, link, trace, analyze, and manage a wide range of diverse textual and graphical information to ensure a project's compliance to specified requirements and standards [44].

The use of requirements management workflows and technologies are not wide-spread in the construction industry and appear to be more common in the civil engineering and infrastructure sectors. Within these sectors, requirements

---

[2]The American Institute of Architects.
[3]The Australian Construction Industry Forum.
[4]The Australasian Procurement and Construction Council Inc.

management tools such as IBM Rational DOORS are relatively common. In the healthcare sector of construction case studies of BIM projects have also reported the use of planning and data management tools software such as dRofus, which have some requirements management capabilities in relation to the architectural design using a bidirectional link between dRofus and the 3D modelling software (e.g., Autodesk Revit and Graphisoft's ArchiCAD). dRofus provides a cloud-based platform and enables a data-centric approach to managing requirements relative to BIM outputs. In this way, client requirements can be captured and the traceability of any changes to the architectural model can be supported. The facility standards of multiple projects can also be managed using the dRofus tool [45]. However, the interactions between multiple dependent requirements remain independent, and links to the model to automate traceability are rare. Further, the use of a Requirements Traceability Matrix (RTM) [27] is typically not systematically applied across the project team in a continuous or integrated way.

Model-based Systems Engineering. Model-based systems engineering (MBSE) is "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [46]. MBSE is aimed at replacing a document-centric approach with a model-centric approach via its full integration with SEP [46]. To reduce the miscommunication and foster the adoption of standard MBSE, SysML was developed as a standard modelling language for the unification of different modelling languages currently used in SE [27, 46]. A common data environment or a central data repository is also required. For example, 3DExperience and TeamCenter are two commonly used platforms supporting SEM activities in complex manufacturing sectors, and are designed to support the management of design and development activities in a single environment [47, 48].

In construction, single environments and enterprise platforms across the supply network are less common. The use of a CDE is growing. Software platforms such as Bentley's, ProjectWise provides a collaborative project environment, where its information management capabilities were developed explicitly for the construction industry [49]. Importantly IFC Standards, developed since the early 1990s, have also provided an open and standardized data model to enable interoperability between BIM software applications. IFC schema supports model-based interoperability [34], and like the SysML standard modelling language provides the means to translate different modelling formats. As a subset of the IFC schema, Model View Definition (MVD) is aimed to define parameters progress [34] and the Information delivery manual (IDM) concept was designed to facilitate interoperability, promote digital collaboration, and provide a basis of high-quality information exchange. However, MVD and IDM are still at an early stage of maturity.

Simulation and Analysis. Simulation and analysis are implemented at both the sub-system level (discipline-specific) and the systems level (multiple-discipline). It is therefore seen as essential to the design of multidisciplinary systems [27]. It enables the achievement of optimal system performance by closely linking the components of different disciplines, supporting the assessment and forecast of the dynamic status of a system and its components [27, 50].

In a model-based construction context, simulation and analyses are primarily undertaken at a discipline level before multiple discipline models are federated. Once federated, the main goal of analysis is the implementation of design coordination and quality assurance processes based on assessments of object interferences using clash detection toolsets. 4D and 5D simulation and analysis methods can be utilized for schedule planning and cost estimation. However, most 3D simulation and analyses methods are siloed activities, making it difficult to assess the dynamic status of the whole design.

Trade-off Analysis. The trade-off analysis is used to support decisions throughout SE process solving conflicts and satisfying both stakeholder requirements and constraints. The goals of trade-off analysis include achieving balanced requirement baselines, selecting the right functional architecture, and identifying the best design solution [27].

In the construction domain, trade-off analysis is known as "Cost/Benefits Analysis", and primarily involves the budget, schedule and quality objectives at the project level [27]. Cost/benefits analyses are most relevant during value engineering (VE) exercises. VE has become a standard practice in construction projects. However, VE is not always fully understood or well executed. Software applications to support collaboration during VE exercises and their outcomes provide a means to record decisions and quantities of elements, track proposed changes, and create an audit trail for later verification. The recent development of cloud-based model data management platforms to support VE provide the ability to access model information, and understand the elements, quantities, and costs being discussed. Yet, these tools encompass only a visual engine to view the model and do not provide the ability to simulate alternative scenarios to explore trade-offs between decision criteria and their impacts.

17.5 Discussion

As discussed in previous sub-sections, the overview of where BIM initiatives are concentrated or partially developed in terms of defined process and protocol, and technological initiatives is illustrated in Table 17.1. The three statuses including ● = growing maturity, ◘ = limited instances, and ○ = an evident gap in BIM processes protocols or technologies. The three statuses reflect the level of development of BIM related initiatives in construction. The ● status means that there are industry level or organizational level standards, guidelines or protocols developed but are as yet unproven across all sectors of the industry; e.g. ISO standards and PAS standards. ◘ status means that there are associated organizational level protocols and documentation reported by researchers in industry case studies. The ○ status means that there are no case studies or relevant industry or organizational documentation.

As a summary of the discussion of the literature presented in Sect. 17.3, Table 17.1 highlights a number of gaps and areas for applying SE approaches and SEM activities to achieve a more integrated approach to design, project delivery and structured information management throughout the life of the project and facility. The importance of project planning is emphasized in the publication of the recent ISO BIM Standards 19650. Despite the increased effort in construction on the development and implementation of process and data standards, a holistic systems approach is lacking. Accordingly, initiatives and guidelines present a fragmented approach to BIM implementation and industry confusion still surrounds methods to support greater levels of data and information quality and accuracy in project delivery. A key example highlighting deficiencies in current BIM implementation methods lies in SE approaches to development phasing specifying tightly couple configuration management activities and software applications for verification and validation activities. However, the linkages between building system decomposition and definition and the verification of requirements, functions, and objects together with their validation against client expectations are largely missing in the construction domain's approach to BIM implementation.

While the ● status represented in Table 17.1 represents growing maturity in some areas, the limited instances ◘ and number of gaps ○ outweigh the patchy development of a methodology to implement BIM to realize the value of building information throughout the life of the project and asset. Key areas for research to address include integrated approaches to (i) development phasing with specific emphasis on configuration management, (ii) a comparable systems engineering

Table 17.1 Systems engineering approaches versus BIM related initiatives

SE approaches		BIM methods, tools and initiatives	
		Process and protocols	Technologies
SEM activities			
Development phasing	Verification	●	●
	Validation	◘	◘
	Configuration management	○	○
Life-cycle integration	Project planning	●	○
	Project monitoring and control	●	◘
Systems engineering process	Requirement analysis	◘	◘
	Functional analysis and allocation	◘	○
	Design synthesis, verification, and validation	◘	○
	System analysis and control	○	○
SEM Enablers			
People	Integrated product teams	●	◘
Process and protocol	Systems integration process	○	○
	SE management plan	◘	○
	Requirements management	◘	◘
Technology	MBSE	◘	●
	Simulation and analysis	○	◘
	Trade-off analysis	○	○

Note ● growing maturity; ◘ limited instances; ○ gap process with particular need to address deficiencies in system analysis and control, and (iii) system management enablers including systems integration processes, requirements management, and trade-off analysis.

17.6 Conclusion

The work presented in this paper is an initial step in a larger research effort to understand the role and better utilize SE and SEM methods to support building information management through-life. Based on the review of current BIM practices and initiatives, a degree of disparate and fragmented approaches to BIM is evident across the different development phases. Gaps in a more systematic approach to BIM implementation and through-life information management are identified. Gaps relate to development phasing, lack of systemic approaches to product and process integration, and system management enablers. However, these gaps reflect a non-exhaustive review of current BIM standards, protocols, processes and documented case studies. Findings are therefore limited. Moreover, the interrelationships of the gaps identified are essential before proffering conclusions. Further, the level of maturity at an organizational level is difficult to estimate due to human factors and variations in BIM competencies. Industry perspectives of both SE, SEM, and BIM are therefore essential to extend this research. Current work is focused on undertaking a more detailed review and comparison of SE, SEM and BIM methods and enablers.

References

1. Hoeber, H., Alsem, D.: Life-cycle information management using open-standard BIM. Eng. Constr. Archit. Manag. **23**, 696–708 (2016). https://doi.org/10.1108/ECAM-01-2016-0023
2. Green, S.D., Newcombe, R., Fernie, S., Weller, S.: Learning Across Business Sectors: Knowledge Sharing Between Aerospace and Construction. The University of Reading, Reading (2004)
3. Whyte, J.K., Hartmann, T.: How digitizing building information transforms the built environment. Build. Res. Inf. **45**, 591–595 (2017). https://doi.org/10.1080/09613218.2017.1324726
4. Eastman, C., Eastman, C.M., Teicholz, P., Sacks, R., Liston, K.: BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. Wiley (2011)
5. Barlish, K., Sullivan, K.: How to measure the benefits of BIM—A case study approach. Autom. Constr. **24**, 149–159 (2012). https://doi.org/10.1016/j.autcon.2012.02.008
6. Love, P.E., Matthews, J., Simpson, I., Hill, A., Olatunji, O.A.: A benefits realization management building information modeling framework for asset owners. Autom. Constr. **37**, 1–10 (2014). https://doi.org/10.1016/j.autcon.2013.09.007
7. Jupp, J.R., Awad, R.: BIM-FM and information requirements management: missing links in the AEC and FM interface. In: Product Lifecycle Management and the Industry of the Future. Springer, Cham, pp. 311–323. (2017) https://doi.org/10.1007/978-3-319-72905-3_28
8. Anderson, A., Marsters, A., Dossick, C.S., Neff, G.: Construction to operations exchange: challenges of implementing COBie and BIM in a large owner organization. In: Construction Research Congress 2012: Construction Challenges in a Flat World, pp. 688–697. (2012) https://doi.org/10.1061/9780784412329.070
9. Jupp, J.R.: Cross industry learning: a comparative study of product lifecycle management and building information modelling. Int. J. Prod. Lifecycle Manag. **9**, 258–284 (2016). https://doi.org/10.1504/IJPLM.2016.080502
10. Boton, C., Rivest, L., Forgues, D., Jupp, J.: Comparing PLM and BIM from the product structure standpoint. In: IFIP International Conference on Product Lifecycle Management. Springer, Cham, pp. 443–453 (2016). https://doi.org/10.1007/978-3-319-54660-5_40
11. Blockley, D.I., Godfrey, P.: Doing it Differently: Systems for Rethinking Construction. Thomas Telford (2000)
12. Aslaksen, E.W., Delamare, M., Fehon, K., Godau, R., Knott, A., Kouassi, A., De Liefde, J.: Guide for the application of systems engineering in large infrastructure projects. INCOSE Infrastruct Work Group San Diego (2012)
13. Whyte, J.: The future of systems integration within civil infrastructure: a review and directions for research. In: INCOSE International Symposium, vol. 26, pp. 1541–1555 (2016) https://doi.org/10.1002/j.2334-5837.2016.00244.x
14. INCOSE.: Systems Engineering Handbook. A Guide for System Life Cycle Processes and Activities, v.3. INCOSE, Seattle, WA, USA (2006)
15. Sage, A.P., Rouse, W.B.: Handbook of Systems Engineering and Management. Wiley (2009)
16. Lindkvist, C., Stasis, A., Whyte, J.: Configuration Management in Complex Engineering Projects. Procedia CIRP **11**, 173–176 (2013). https://doi.org/10.1016/j.procir.2013.07.046
17. Morris, P.W.: The Management of Projects. Thomas Telford (1997)
18. Whyte, J., Stasis, A., Lindkvist, C.: Managing change in the delivery of complex projects: configuration management, asset information and 'big data'. Int. J. Proj. Manag. **34**, 339–351 (2016). https://doi.org/10.1016/j.ijproman.2015.02.006
19. Xu, X., Ma, L., Ding, L.: A Framework for BIM-Enabled life-cycle information management of construction project. Int. J. Adv. Robot. Syst. **11**, 126 (2014). https://doi.org/10.5772/58445
20. Zadeh, P.A., Wang, G., Cavka, H.B., Staub-French, S., Pottinger, R.: Information Quality Assessment for Facility Management. Adv. Eng. Inform. **33**, 181–205 (2017). https://doi.org/10.1016/j.aei.2017.06.003
21. Hedberg, T., Feeney, A.B., Helu, M., Camelio, J.A.: Toward a lifecycle information framework and technology in manufacturing. J. Comput. Inf. Sci. Eng. **17**, 021010 (2017). https://doi.org/10.1115/1.4034132

22. Lemberger, I.D., Erasmus, L.D.: Systems engineering management process maturity of South African manufacturing organisations. In: Management of Engineering and Technology (PICMET), 2014 Portland International Conference. IEEE, pp. 2371–2380 (2014)
23. ProRail, Rijkswaterstaat, Bouwend-Nederland, ONRI (2013) Guideline Systems Engineering for Public Works and Water Management, Version 3
24. Matar, M., Osman, H., Georgy, M., Abou-Zeid, A., El-Said, M.: A systems engineering approach for realizing sustainability in infrastructure projects. HBRC. J. **13**, 190–201 (2017). https://doi.org/10.1016/j.hbrcj.2015.04.005
25. de Graaf, R.S., Vromen, R.M., Boes, J.: Applying systems engineering in the civil engineering industry: an analysis of systems engineering projects of a Dutch water board. Civ. Eng. Environ. Syst. **34**, 144–161 (2017). https://doi.org/10.1080/10286608.2017.1362399
26. de Graaf, R.S., Voordijk, H., den Heuvel, L.: Implementing systems engineering in the civil engineering consulting firm: an evaluation. Syst. Eng. **19**, 44–58 (2016). https://doi.org/10.1002/sys.21336
27. Locatelli, G., Mancini, M., Romano, E.: Systems engineering to improve the governance in complex project environments. Int. J. Proj. Manag. **32**, 1395–1410 (2014). https://doi.org/10.1016/j.ijproman.2013.10.007
28. BSI (2013) PAS 1192-2: 2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling. The British Standards Institution
29. BSI (2014) PAS 1192-3: 2014 Specification for information management for the operational phase of assets using building information modelling. The British Standards Institution
30. Defense Acquisition University: Systems engineering fundamentals. Fort Belvoir, VA., USA (2001)
31. Xu, Y., Malisetty, M.K., Round, M.: Configuration management in aerospace industry. Procedia. CIRP. **11**, 183–186 (2013). https://doi.org/10.1016/j.procir.2013.07.052
32. FHWA: Systems Engineering for Intelligent Transportation Systems (2007)
33. Bolpagni, M., Ciribini, A.L.: The information modeling and the progression of data-driven projects. In: CIB world building congress. pp. 296–307 (2016)
34. Boton, C., Rivest, L., Forgues, D., Jupp, J.: A comparison of shipbuilding and construction industries from the product structure standpoint. Int. J. Prod. Lifecycle Manag. 11–2 (2018)
35. AIA: E202-2008 Building Information Modeling Protocol Exhibit. American Institute of Architects, Washington, DC (2008)
36. AEC (CAN) (September) BIM Protocol—Implementing Canadian BIM Standards for the Architectural, Engineering and Construction Industry Based on International Collaboration, V 2. CanBIM, Toronto
37. BIMForum (2015) Level of Development Specification. For Building Information Model, V 2015
38. AIA (2007) Integrated Project Delivery: A Guide. Version 1
39. ACIF, APCC (2014) Project Team Integration Workbook
40. OGC: Achieving Excellence Guide 5 - The Integrated Project Team (2007)
41. Browning, T.R.: Designing System Development Projects for Organizational Integration. Syst. Eng. **2**(4), 217–225 (1999)
42. Davies, A., Mackenzie, I.: Project complexity and systems integration: constructing the London 2012 Olympics and Paralympics Games. Int. J. Proj. Manag. **32**, 773–790 (2014). https://doi.org/10.1016/j.ijproman.2013.10.004
43. McArthur, J.J., Sun, X.: Best practices for BIM execution plan development for a public-private partnership design-build-finance-operate-maintain project. WIT Trans. Built. Environ. **149**, 119–130 (2015)
44. IBM Rational DOORS. https://au.mathworks.com/products/connections/product_detail/ibm-rational-doors.html. Accessed 27 Apr 2018
45. Product | dRofus. http://www.drofus.no/en/product.html. Accessed 27 Apr 2018
46. INCOSE T.: Systems Engineering Vision 2020. INCOSE-TP-2004-004-02), http://www.incose.org/ProductsPubs/pdf/SEVision2020_20071003_v2_03.pdf (2007)
47. What is Teamcenter? (or, Teamcenter explained)—Tata Technologies PLM Solutions. http://blog.myigetit.com/2016/08/17/what-is-teamcenter-or-teamcenter-explained/. Accessed 27 Apr 2018
48. DEXPERIENCE® Platform - Dassault Systèmes®. https://www.3ds.com/products-services/3dexperience/. Accessed 27 Apr 2018
49. ECS - ProjectWise. http://www.cadsolutions.com.au/projectwise.shtml?gclid=CjwKCAjwlIvXBRBjEiwATWAQIuTS3gvvdiuIopJk_VMP8Qd7gi9DT1o-294NovliMyI0e96bSebV2xoC4p0QAvD_BwE#. Accessed 27 Apr 2018
50. Sinha, R., Paredis, C.J., Liang, V.-C., Khosla, P.K.: Modeling and simulation methods for design of engineering systems. J. Comput. Inf. Sci. Eng. **1**, 84–91 (2001). https://doi.org/10.1115/1.1344877