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Developing BIM Thinking: Fundamental Objectives and Characteristics of BIM to Think Critically About in BIM Research and Implementation

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Abstract. This article proposes pathways towards developing BIM thinking as a set of objectives and characteristics that allow revisiting the grounds and principles on which one can reason about BIM, irrespective of the specific applications or tools. The article looks into questions such as– Why do we need BIM thinking, and why now? What should we look for in BIM thinking, and how? The research applies abductive reasoning for qualitative grouping and classification of the preprocessed data collected from the existing literature review articles and BIM glossaries, combined with peer feedback from workshops and discussions. The fundamental objectives and characteristics to be considered in BIM thinking include representation, documentation, transactions and exchange, decision support, standardization, knowledge and information management, automation, and ecosystem and systems. Since the hope of the future transformation of the construction industry is largely pinned on a range of digital technologies, BIM thinking should facilitate informed decisions about the ways forward.

Keywords: BIM thinking, BIM framework, Fundamental objectives.

1 Introduction

Building Information Modeling (BIM) has been one of the most popular topics in the literature on digitalization and construction management in the last decade or more. BIM still remains at the centre of the projected future of digital construction e.g. [1]. Despite this growing BIM research and development, and barring the seminal foundational works of the pre-BIM era from 1970s to 1990s [2,3,4,5,6], BIM research has predominantly been applied research, with numerous application areas and pilot studies, but with limited fundamental or theoretical discussion. In addition, some authors have questioned the extent of realized benefits of BIM in practice [7,8]. Thus, it appears that the applied BIM research could benefit from a revisit of the theoretical foundations of BIM, as a step towards ‘BIM thinking’. Therefore, this article focuses on the propositions and pathways towards developing BIM thinking as a set of objectives and characteristics that form the contemporary theoretical understanding of BIM.

1.1 Why do we need BIM thinking? And, why now?

During the pre-BIM research, when early conceptualization and prototyping of building product models was in progress, the leading researchers [2,3,4,5,6] investigated diverse theoretical approaches, conceptual frameworks and requirements of the desired system, including database theories, ontological frameworks, product data modelling, geometric modelling– space boundaries, topological networks, class hierarchies, knowledge-based systems, programming language theory, abstraction principles, system architecture and process modelling.

Though the pre-BIM literature built the theoretical and conceptual foundations that led to the conception and development of BIM tools and applications, the mainstream BIM literature since 2004 has not shown adequate theoretical review and reflection from the applied research and practice to revisit and improve our conceptual understanding of BIM, barring a few noticeable exceptions. For instance, Succar's [9] highly cited article that emphasized the need for a research framework went on to identify conceptual dimensions of the BIM research landscape, including research fields, stages, steps and lenses. Though this conceptual and theoretical work made a significant contribution in 'scene-setting' to understand and guide BIM research trends, the discussed concepts pertain to research areas and trends, and do not adequately deal with underlying foundations of BIM itself. This is further reflected in the follow-up articles of Succar and colleagues [9,10], which focus on conceptual dimensions of BIM macro-adoption patterns [10], maturity models and capability matrix [11]. In a similar context, there is considerable effort in developing BIM guidelines and execution plans, with more recent focus on structured classification of the various factors and use cases towards developing a common language of BIM purposes and objectives [12]. Thus, the theoretical focus of these researchers pertains to what Singh and colleagues [13,14] term as the BIM ecosystem, and not BIM itself. That is, rather than seeking the underlying foundations on which the workings of BIM applications can be explained, these articles discuss the conceptual frameworks related to the products, processes, people and policies that determine adoption, execution and growth of BIM [9].

In contrast, the discussions around BIM applications and tools have mostly continued around data models, ontologies, geometrical modeling, information exchange and semantics, but there have been limited attempts at theory building. Nonetheless, with greater maturity and hands-on experience with BIM, questions confronting the future of BIM are beginning to emerge e.g. [15], which necessitates a relook at the basics. For instance, Turk [15] recently wrote about the ten key questions confronting the future of BIM research, framing his discussion around the Function-Behaviour-Structure (FBS) ontology [16]. Turk [15] puts emphasis on the need to understand the chain of reasoning from the functions of BIM; the structure of BIM, i.e. the way it is realized, and; the behavior of BIM, i.e., how it works in different contexts. Turk further discusses how the context in which BIM is used will influence the future directions, implicitly noting the connection between BIM and the BIM ecosystem.

The effort towards BIM thinking or 'how to critically think about BIM' should be seen as an indicator of maturity in evolution of BIM as a discipline, analogous to other thinking paradigms in complementary disciplines such as engineering design, computation and systems engineering, where we have recently seen the emergence of 'Design thinking', 'Computational thinking' and 'Systems thinking' frameworks that

capture the understanding of the key objectives and characteristics underpinning the respective disciplines. This article has similar objectives, recognizing that by now we have adequate practical experience with BIM applications and tools to critically reflect on and outline the key characteristics that underpin BIM applications and tools. Such a reflective, abductive theory building process should help improve and complement the conceptual and prescriptive theoretical foundations built in the pre-BIM era.

1.2 What should we look for in BIM thinking? And, how?

Given that BIM research has expanded across several themes and areas [17], there are various potential pathways to approach BIM thinking. Nonetheless, before we look into the potential pathways, it is desirable to establish the process, the requirements, and the goals and objectives. What should BIM thinking help us with? How should we go about developing BIM thinking? What do we start with?

BIM thinking should provide the grounds and principles on which one can reason about the fundamental objectives and characteristics of BIM, irrespective of the specific application. For instance, as an analogy, Figure 1 shows different machine tools - a pair of scissors, a wheelbarrow and a tongue, which share the same underlying principle of Lever design. That is, irrespective of the use cases and applications of a lever, we can reason the design and working of the system in terms of the force applied, fulcrum, and the force produced following established computable principles. While it may be challenging to reach this level of precise theoretical working principle for BIM, given that it goes beyond physical laws to socio-cognitive aspects of human interaction, at least the endeavor should be to identify the key objectives and characteristics that are fundamental across all BIM applications.



Fig. 1. Fundamental principles of lever design, independent of the use case and application area.

2 What should be the research approach and methodology?

There is a set of prescriptive theoretical foundations and concepts from the pre-BIM era. In contrast, a complementary approach should independently build on the observations and findings from practical implementation and usage of BIM tools and applications. Such observations and findings are reported in the BIM literature, guidelines and execution plans, reviews, and community forums. In addition, users and experts can provide feedback and insights. Therefore, this research builds on the existing literature, BIM glossaries, as well as feedback from workshops and group discussions.

In order to conduct a thematic grouping and classification of the data to identify BIM objectives and characteristics, instead of collecting the data through another comprehensive literature review, the author builds on a preprocessed dataset by aggregating the findings from existing review articles [17, 18, 19, 20] and other sources (e.g. [12],

www.bimexcellence.org) that have systematically identified the keywords and themes associated with BIM. In addition, some of the notable articles that list the benefits of BIM [21,22,23,24] were also reviewed for keywords.

Since the thematic grouping and classification of the dataset was done qualitatively, the author relied on abductive reasoning to infer and trace each of the keywords and themes in the dataset to their fundamental objectives and characteristics. Abductive reasoning allows best possible explanation and inference when the observations cannot be inferred with deductive certainty.

The identified objectives and characteristics have also been informed by group discussions and peer feedback via workshops and lectures over the last four years, including lectures and workshops in international BIM Summer Schools (2016-2019).

3 What are the objectives and characteristics identified so far?

Based on the qualitative grouping and classification, eight fundamental objectives and characteristics of BIM are identified— representation, documentation, transactions and exchange, decision support system (DSS), standardization, knowledge and information management (KIM), automation, and ecosystem and systems.

Figure 2 uses the identified objectives and characteristics to group and classify some of the commonly posited benefits of BIM, such as visualization, coordination and clash detection, consistent drawings, building design, as-built model, building assembly, construction sequencing, spatial program and massing studies, quantity take-offs, model based estimation, feasibility studies, design options and alternative development, direct fabrication, environmental analysis, code review, facilities management, forensic analysis, logistics and supply chain, and retrofitting and recycling [21,22,23,24].

Similar to the classification of BIM benefits shown in Figure 2, the BIM related terms and themes listed in other notable sources were found to be classifiable according to the eight BIM objectives and characteristics proposed in this paper. Figure 3 shows how many terms in these sources primarily associate with which objective or characteristic. For the purpose of this paper, the distribution patterns seen in Figure 3 will not be discussed any further, but it suffices to show that the identified objectives and characteristics seem adequate to classify all the BIM related terms and themes.

The Penn State BIM Execution Plan [12] originally listed twenty-five use cases while the BIME Initiative (www.bimexcellence.org) lists fifty-two general model uses and seventy-three domain model uses. The authors of the Penn state Execution Guide also noted the need for more structured approach to identifying the BIM uses, classifying BIM uses in terms of the BIM Use purposes (gather, generate, analyze, communicate and realize) and characteristics (facility element, facility phase, discipline, and level of development) [12]. On the other hand, Succar et al in the BIME initiative (www.bimexcellence.org) have put together a list of more than seven hundred keywords and terms in the BIM glossary. In addition, numerous BIM topics and themes have been identified through systemic literature reviews [17,18,19,20]. For example, [17] identified BIM research themes and areas at different levels of granularity.

Thus, it can be seen that the keywords and themes associated with BIM, as identified by authors who have previously conducted systemic and comprehensive review of the BIM literature, can be grouped and classified according to the eight objectives

and characteristics. This supports the claim that these are the fundamental objectives and characteristics of BIM.

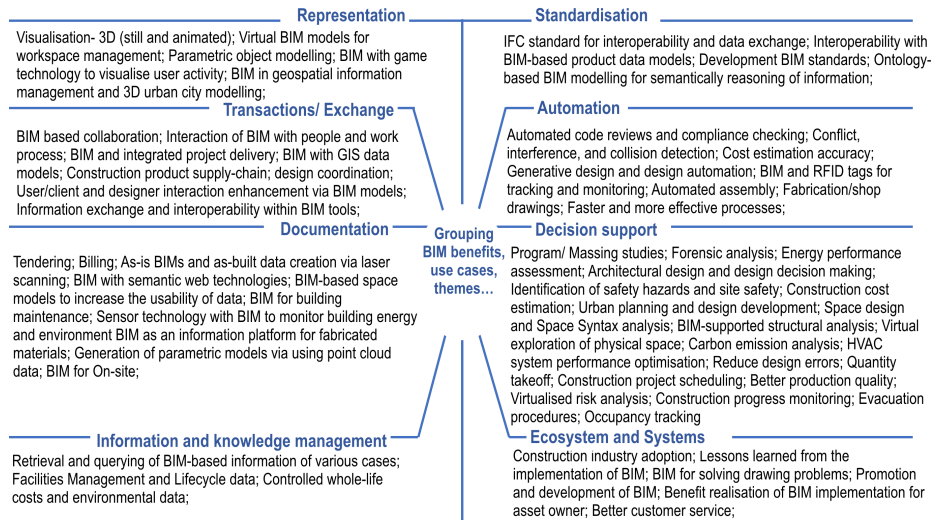


Fig. 2. Fundamental objectives and characteristics of BIM based on qualitative clustering

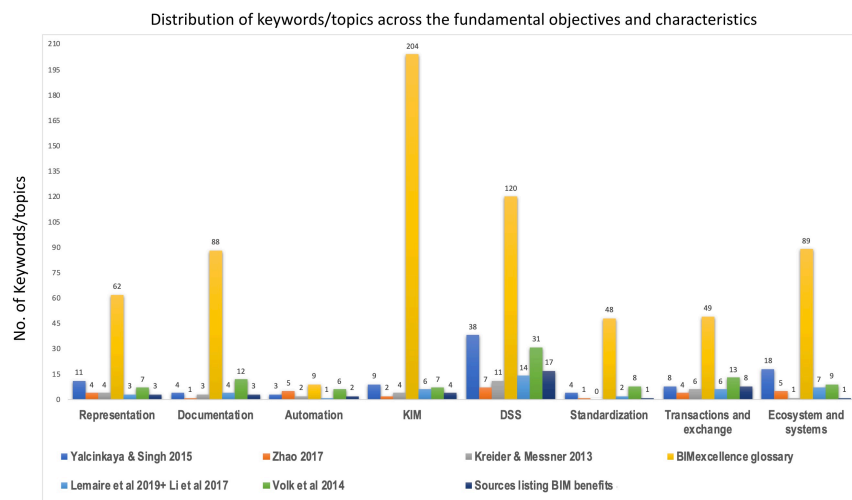


Fig. 3. Distribution of keywords/ topics across the fundamental objectives and characteristics

Before we expand on each of the objectives and characteristics, it is useful to go back to some of the notable definitions of BIM to identify the keywords in these definitions.

The National Institute of Building Sciences (NIBS) defines BIM as “a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis

for decisions during its lifecycle from inception onward.” The NIBS definition of BIM remains broad, putting emphasis on digital representation, information and knowledge sharing, and decision making, rather than going into specifics of how these functional characteristics are realized and for what use cases. Nonetheless, in the NIBS documents the text that follow do outline specific prerequisites and purposes such as digital database, intelligent data including product data and other specifications, 2D drawings to 3D elements, animations, and 4D-5D capabilities such as scheduling, estimation, etc.

Similarly, [23] define BIM as modeling technology and associated set of procedures to produce, communicate, and analyze building models. The definition is further qualified to state that the building models are characterized by (1) building components represented with intelligent digital representations (objects) with computable graphics, data attributes, and parametric rules (2) components that include data needed for analyses and work processes such as takeoff and energy analysis, (3) consistent and non-redundant data, and (4) coordinated data. This definition also puts emphasis on the characteristics and objectives, rather than the specific purposes. The additional statements highlight the basic technical criteria of an intelligent object-based representation with attributes, parametric relationships and rules.

In contrast, the Penn State guide [12] defines BIM as “the act of creating an electronic model of a facility for the purpose of visualization, engineering analysis, conflict analysis, code criteria checking, cost engineering, as-built product, budgeting and many other purposes.” The guide also defines BIM Use as “a method of applying BIM during a facility’s lifecycle to achieve one or more specific objectives.” Thus, the Penn State guide, aimed at practitioners, defines BIM in terms of its purposes and use cases rather than its underlying characteristics.

The keywords in the three representative definitions are captured within the identified fundamental characteristics and objectives of BIM. However, it is notable that some aspects of BIM have dominated the narrative in practice rather than a more fundamental understanding of BIM. For example, though the definitions emphasize digital representation, the dominant discussion in practice is specific to 3D Visualization and 3D models. It is not uncommon among practitioners to think of BIM synonymously with 3D models and 3D visualization. Similarly, others consider ‘I’ as the single most important aspect of BIM, underplaying the other characteristics.

Therefore, it is proposed that we need a course correction in the common narrative and understanding of BIM to foster a more fundamental and broader way of thinking about BIM such that the wider potential of BIM can be realized in practice. Figure 4 illustrates how each of the objectives and characteristics of BIM hold multiple dimensions and aspects to consider.

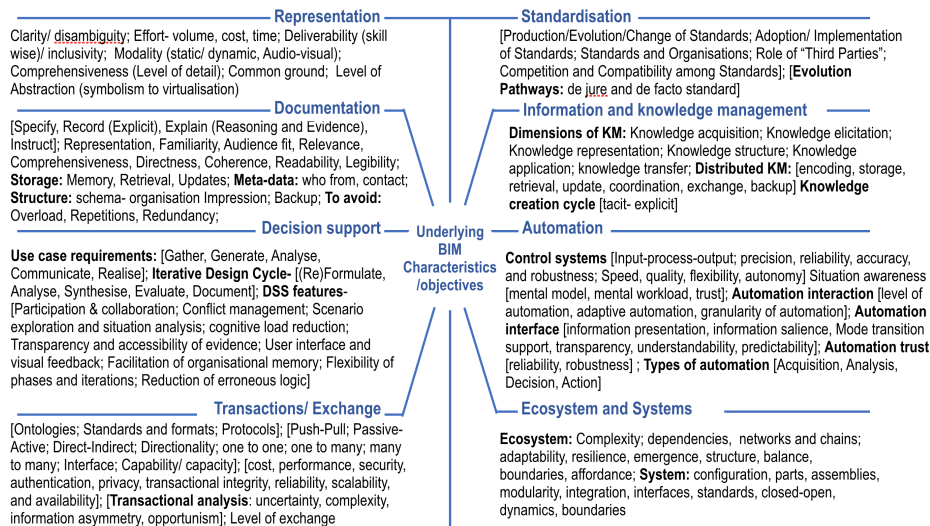


Fig. 4. Some aspects and dimensions to consider for the identified objectives and characteristics

3.1 What is desired in a representation? And, what does it mean in the context of BIM?

Representation goes beyond visualization and 3D or 2D discussions. Representation can be for communication of ideas, for externalization of ideas, for documentation, etc e.g. [25,26,27,28]. The attributes and requirements of the representation may vary with the purpose, but in general it can be stated that:

- Representation should be clear and disambiguous, which requires adequate level of detail. Typically, the less abstract a representation, the greater is the clarity. While symbolic representations such as drawings are abstractions, object-based 3D representations and virtual models are less abstract or ambiguous.
- In a typical resource-constrained work environment, creating representations should require as little effort as possible in terms of cost, volume and time without compromising on the clarity and required level of detail [29].
- In a team environment, the mode of representation should be inclusive such that the stakeholders are able to create, understand and share the representations. The more demanding a representation gets in terms of the skills and competence required to work with, the greater will be the challenge to diffuse and use it across the team.
- On one hand representations should be as comprehensive as needed, but at the same time require as little effort, time, skills and cost to produce and use. There is a trade-off between the level of detail and how well the details serve the intended purpose.
- One of the factors determining the level of detail and the extent of abstraction in a representation is common ground held between producers and consumers of the representation and the context [30]. Standards provide one such mechanisms for creating a common ground. Languages are a good example of symbolic representations that work well because of common ground shared within a society. The further we

move away from abstraction to virtualization, the easier it is to have a common ground. Nonetheless, such a move would typically require higher volume, effort, cost, time and skill.

For example, in Figure 5, from left to right we move from a 2D symbolic representation to 3D perspective view to an object-based model with object attributes.

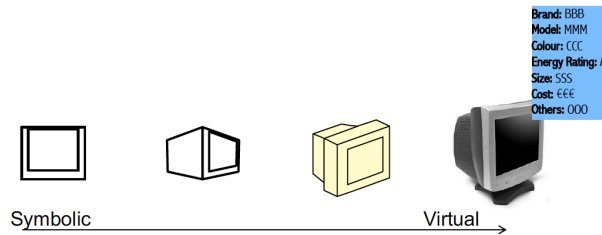


Fig. 5. Evolution of digital representation from symbolic drawings to virtual models

As evident in Fig. 5, the representations on the right are less ambiguous. This shift from symbolic to virtual representation is akin to the evolution of digital representation in construction from 2D drawings to BIM. Nonetheless, as we move from left to right, the representations increasingly become more demanding in terms of the time, volume, skills and cost of production. Creating a 2D rectangle is easier and faster for most people when compared to creating a 3D perspective. Thus, unless it is necessary and significant value add to create a very detailed representation, a simpler representation will typically save cost, time, and effort. This is where the evolution of BIM has played a critical part. If the details of an object exist apriori in the object library, producing a detailed 3D representation is just a click away. At the same time, the processing power and data storage in computers have grown significantly to process high volumes of data, allowing the production of all this detailed data without much concern for volume. Consequently, the factors determining the choice of representation have gradually shifted from the challenges in production of the representation to the purpose and consumption of the representations. The questions have shifted from how to why, for whom, and for what? Traditionally the representations were meant for human-to-human (H2H) communication of intent or for instructions or for interpretation and feedback. The designers produced representations for the clients to understand the design and for the engineers to build. As we move towards automation, representations may not only be intended for H2H communication, but also for human-to-machine (H2M), machine-to-machine (M2M), and machine-to-human (M2H) communication. The role of representation is growing beyond the communication of intent to include computational processing and the command for production. As a result, aspects such semantics, machine readability and accuracy of the representation are becoming critical [31].

3.2 What is desired in documentation? And, what does it mean in the context of BIM?

Documentation is another primary objective of BIM applications. Turk [15] suggests that the primary function of BIM is to serve as a database. Intelligent documentation of

the data across different representational modes allow consistency, history tracking, and archiving. Following are some of the key aspects of documentation

- Documentation should provide specifications, explicit records, adequate explanation to facilitate reasoning and evidence, and instructions relevant to the activities and tasks. The record should have content, structure and context [32].
- Some of the aspects to consider in documentation include, the type of representation, familiarity of audience with the content, relevance of the content to the purpose, and characteristics such as comprehensiveness, directness, coherence, readability and legibility of the content [33,34].
- From the perspective of data management and organization, factors include storage related aspects such as memory, retrieval and updates; meta-data such as authors details; representational and structural issues such as schema; and, backup.
- Documentation should not have information overload, repetitions and redundancy.

Several aspects of documentation listed above are already noted in the BIM literature. There is extensive discussion on meta-data, representation and schema e.g. [35]. Issues on information requirements, specifications and archiving have been emphasized in execution plans and guidelines. Thus, this line of BIM thinking from documentation perspective can provide useful insights. Who is the documentation for? Who requires what meta-data, explanation and reasoning? Documentation can also be for human users as well as for automated reasoning by machines, in which case machine readability and semantics is once again important.

3.3 What is desired in BIM as a Decision Support System (DSS)?

Given the range of BIM tools and applications, BIM means different things to different stakeholders [36], but in almost all cases it is more than just a database. From the early design phase to the facilities management and operations phase, BIM is envisioned to support one or more of the decision-making activities, ranging from clash detection, cost analysis, energy simulations and analysis, other performance analyses to assessing construction deviations, tracking building performance, and condition monitoring. That is, broadly speaking, one of the primary objectives of BIM is to serve as a DSS. Therefore, following are some of the desired aspects of BIM as a DSS

- Kreider et al. [12] summarize the use cases broadly under the objectives of gathering, generating, analysing, communicating, and realising.
- BIM should support the iterative design decision process, including problem formulation and reformulation, analysis, synthesis, evaluation, and documentation [16].
- From a groupware and organizational perspective, DSS should have features that support participation and collaboration, conflict management, scenario exploration and situation analysis, reduction of cognitive load, transparency and accessibility of evidence, user interface and visual feedback, facilitation of organisational memory, flexibility of phases and iterations, and reduction of erroneous logic [37,38,39].

Several aspects of DSS are already noted in the BIM literature, ranging from conflict management, collaboration and visual feedback. Other aspects such as cognitive load and facilitation of organizational memory have not been adequately investigated.

3.4 How is transaction and exchange fundamental to BIM? What is expected in terms of transaction and exchange?

Facilitating communication, collaboration and exchange is often emphasized as one of the main objectives of BIM e.g. [36]. This has been articulated in several ways, including the emphasis on exchange formats on one hand [40] to the shift in perspective from lonely BIM to social (collaborative) BIM [41]. While the emphasis on collaborative BIM and exchange is unquestionable in a team environment, unlike traditional design and drafting tools, BIM also provides an interactive media where the designer also collaborates and transacts with the tool, which can provide feedback, highlight human errors, auto-correct and auto-complete actions, etc. That is, collaboration and exchange is not limited to H2H interactions, but there is collaboration between the tools and the users as well [42,43]. Thus, transactions and exchange are also fundamental to BIM applications. Following are some of the key aspects to consider:

- Transactions and exchange are facilitated by agreed protocols and established standards, formats and ontologies e.g. [40].
- Transactions can be evaluated in terms of cost, performance, security, authenticity, privacy, transactional integrity, reliability, scalability and availability [44].
- Transactional analysis also includes a review of uncertainty, complexity, information asymmetry and opportunism [45]. For example, information asymmetry and directionality of transactions can be assessed in terms of interfacing mechanisms, push and pull, passive and active, etc.

While aspects such as protocols, formats, standards, etc are some of the most commonly discussed topics in the BIM literature, a more fundamental transactional analysis dealing with aspects such as information asymmetry, opportunism, etc can provide further insights into BIM applications and processes.

3.5 In what ways is standardization fundamental to BIM?

Plenty has been written about BIM standards and standardization [46,35,40,47,48]. Following are some of key aspects to consider

- Standards exist in all socio-technical systems, ranging from informal norms to formal specifications—equally applicable to products, processes, people and policies e.g. [49,50,51,52].
- Standards tend to reduce uncertainty by regularizing things. There is a trade-off between routine and non-routine, determining the degrees of freedom and flexibility.
- In a complex system, standards are particularly critical at the interfaces to facilitate transactions, scalability, flexibility and cross-functionality [53].
- Factors that determine the impact of a standard include the production and evolution of standards, the adoption and implementation of standards, the number of competing and compatible standards [51,54,55].

Some aspects of standardization such as data formats and exchange standards have dominated the BIM discourse. Object libraries and standard components may influence standardization and uniformity in the design outcomes. In contrast, with increasing integration of generative design systems with BIM applications, there is more to think about the roles and opportunities for BIM standards in routine and nonroutine design.

3.6 How is information and knowledge management (KIM) fundamental to BIM? And, what is expected?

Several experts and practitioners argue that BIM should be seen as ‘Building Information Management’. Information management (IM) is evidently one of the fundamental objectives of BIM [56]. Since BIM applications are meant to have object attributes, rules and relationships, capturing domain knowledge is also integral to BIM e.g. [57,58,59,60,61]. Hence, following are some of the points to consider from an information and knowledge management (KIM) perspective

- From the perspective of IM, aspects such as Create-Read-Update-Delete (CRUD) operations, storage and retrieval of information are also related to documentation.
- Dimensions of KM to consider include knowledge acquisition, elicitation, representation, structure, application and transfer e.g. [62,63].
- Sociotechnical systems typically involve distributed KIM, comprising of activities related to encoding, storage, retrieval, update, coordination, exchange and backup for data, information, and knowledge [64,65].
- While the tacit-explicit knowledge creation cycle provides continuous improvement, there is continuing need for updates and upgrades [66].

Several aspects of KIM are commonly considered in the BIM literature. Nonetheless, some aspects such as the CRUD operations, knowledge structure, application and transfer have dominated the discourse. Some factors related to distributed KIM such as coordination and exchange have been extensively discussed [36]. However, further insights can be gained by looking deeper from the perspective of KIM e.g. [25,67]. For example, what role does BIM play in the knowledge creation cycle?

3.7 How is automation fundamental to BIM? What does it mean?

Automation is subsumed in multiple BIM features and use cases. From intelligent documentation to clash detection to performance analyses to generative design to the creation of as-built models, automation is ingrained in BIM with the objective to reduce manual labour and human error. Thus, automation remains one of the fundamental objectives of BIM. Some of the key aspects to consider in terms of automation include

- Automation from a control systems perspective takes into account the Input-process-output activities. Some of the measures and performance indicators are precision, reliability, accuracy, and robustness, besides process measures such as speed, quality, flexibility, and autonomy [68].

- Automation design considerations include the assessment of interaction in terms of the level of automation (how much?), adaptivity of automation (when?), and the granularity of automation (for what tasks?) [68].
- Factors to consider with respect to automation interface include information presentation, information salience, mode transition support, transparency, understandability, and predictability [68,69].
- In terms of situation awareness, the types of automation goals include acquisition, analysis, decision, and action [68,69,70].

Automation is integral to BIM applications, both as a requirement and as an objective. BIM should also support automation in the production and construction process.

3.8 Why is ecosystem and systems view fundamental to BIM?

BIM should be seen from an ecosystem perspective with a range of products, processes and people that co-evolve [13,14,71]. Therefore, if we are seeking the fundamentals of BIM thinking, the systems and ecosystem perspective must be considered.

- Structure and links between the constituents and parts of the system.
- Dependencies and relationships between the parts and constituents of the system.
- System boundaries, which can be analyzed at micro to macro levels.
- Adaptability, resilience, flexibility and stability of the ecosystem.
- Emergence, whereby unexpected and new opportunities continue to emerge.

The ecosystem perspective of BIM has been discussed extensively, ranging from BIM adoption models and frameworks, execution plans and maturity models, to tools matrix and product suites, the recognition of BIM ecosystem is widespread.

4 What can we conclude, and what next?

The qualitative analysis revealed a set of objectives and characteristics that can be claimed to be fundamental to BIM thinking. One of the ways to work with these objectives in any BIM research or implementation scenario is to ask the 5Ws1H (Who? Why? What? When? Where? and How?) questions for each, Figure 6. For example, who needs the representation or who has to produce it? Why and what for? When is it needed and where? And, how is it going to be produced, delivered and consumed? It is also important that the questions not only consider the human actors but also the non-human actors including software applications, machines and smart equipment and devices.

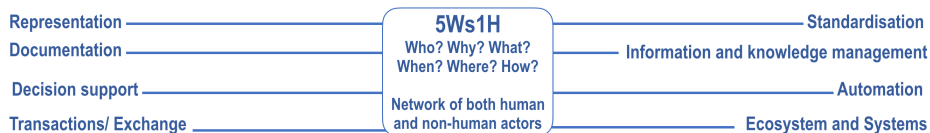


Fig. 6. Working with the fundamental objectives using the 5Ws1H questions

In addition, following points must be noted:

- Some of the basic requirements for a system to be considered within the purview of BIM such as object-based model with attributes, parameters, rules and relationships is considered as technical prerequisites and requirements, rather than objectives or characteristics. A significant part of the pre-BIM theoretical and conceptual work fall in this category. However, a comprehensive comparison and theoretical benchmarking of where we are (based on observations and inferences) and what was conceived in the pre-BIM and early development stages of BIM is still to be done.
- The identified objectives and characteristics identified are not mutually exclusive. For example, there is evidently close relationships between representation and documentation, or representation, documentation and KIM. While we have identified a set of fundamental objectives and characteristics in BIM thinking, we need further research to understand and establish the relationships between them.
- While a set of objectives and characteristics have been identified, further research is needed to assess if these are the ‘necessary and sufficient’ set of fundamental objectives and characteristics to think about BIM or not.
- Since the set of objectives and characteristics are identified through abductive grouping and classification, without a theoretical or conceptual framework to begin with, it will be useful to benchmark and assess these aspects of BIM thinking against complementary thinking paradigms of design thinking [72], computational thinking [73] and systems thinking [74] to get further insights. Design thinking broadly views design as a problem-solving approach independent of the nature of the problem. Thus, design thinking is relevant when we approach BIM as a solution to the varied problems that are derived from the use cases. Since BIM is inherently based on a computational foundation, computational thinking is relevant because it involves a set of problem-solving approaches that express problems and solutions in ways that a computer can aid. And finally, BIM can be seen from a systems perspective, which means we can also adopt systems thinking which provides a holistic approach that focuses on the way that a system's constituent parts interrelate and how systems work over time and within the context of larger systems.

References

1. Gerbert, P., Castagnino, S., Rothballer, C., Renz, A., Filitz, R.: Digital in engineering and construction, The Transformative Power of BIM, The Boston Consult. Group, MA (2016).
2. Eastman, C., Fisher, D., Lafue, G., Lividini, J., Stoker, D., Yessios, C.: An Outline of the Building Description System, Res. Report No. 50, Inst. of Phys. Planning, CMU (1974).
3. Eastman, C., Augenbroe, G.: Product Modeling Strategies for Today and the Future, Proc. of CIB W78 works. on the lifec. of Const. IT innov's, Sweden, 3-5 June, 191-208 (1998).
4. Björk, B., Penttila, H.: A scenario for the development and implementation of a building product model standard, *Advances in Engineering Software*, 11(4), 176–187 (1989).
5. Björk, B.: A conceptual model of spaces, space boundaries and enclosing structures, *Automation in Construction* 1(3). 193–214. (1992a)
6. Björk, B.: A unified approach for modelling construction information, *Building and Environment* 27 (2), 173-194, (1992b).

7. Barlish, K., Sullivan, K.: How to measure the benefits of BIM—a case study approach, *Automation in Construction* (24), 149–159 (2012).
8. Herva, M., Singh, V.: Assessing gaps and opportunities in measuring the benefits of BIM in infrastructure design projects: what can we consider before, during and after the project? *International Journal of Product Lifecycle Management* 11(4), 326–349 (2018).
9. Succar, B.: Building information modelling framework: a research and delivery foundation for industry stakeholders, *Automation in Construction*, 18(3), 357–375 (2009).
10. Succar, B., Kassem, M.: Macro-BIM adoption: conceptual structures, *Auto. in Construction*, 57(9), 64–79 (2015).
11. Succar, B.: Building information modelling maturity matrix. In J. Underwood, & U. Isikdag (Eds.), *Handbook of research on BIM and constr. informatics: concepts and tech.* (pp. 65–103). Info. Sc. Reference, IGI Publishing. doi:10.4018/978-1-60566-928-1.ch004 (2010).
12. Kreider, Ralph G., Messner, J. I.: *The Uses of BIM: Classifying and Selecting BIM Uses. Version 0.9*, Sept, PennState, Univ. Park, PA, USA. <http://bim.psu.edu> (2013).
13. Singh, V.: BIM ecosystem research: what, why and how? Framing the directions for a holistic view of BIM, in Harik, R., Rivest, L., Bernard, A., Eynard, B. Bouras, A. (Eds), *Product Lifecycle Management for Digital Transformation of Industries, PLM IFIP Advances in Information and Communication Tech.*, Vol. 492, Springer, Cham (2016).
14. Gu, N., Singh, V., London, K. BIM ecosystem: the coevolution of products, processes, and people, in Kensek, K. and Noble, D. (Eds), *BIM in Current and Future Practice*, John Wiley & Sons, NJ, pp. 197–211 (2014).
15. Turk, Ž.: Ten questions concerning building information modelling. *Building and Environment*. 107. 10.1016/j.buildenv.2016.08.001 (2016).
16. Gero, J.S.: Design prototypes: A knowledge representation schema for design. *AI Magazine* 11(4), 26–36 (1990).
17. Yalcinkaya, M., Singh, V.: Patterns and trends in building information modeling (BIM) research: a latent semantic analysis, *Automation in Construction*, 59(11), 68–80 (2015).
18. Li, X., Wu, P., Shen, G. Q., Wang, X., Teng, Y. (2017) Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach, *Automation in Construction*. Elsevier, 84(10), pp. 195–206.
19. Zhao, X. (2017) A scientometric review of global BIM research: Analysis and visualization, *Automation in Construction* 80(4), 37–47.
20. Lemaire, C., Rivest, L., Botton, C., Danjou, C., Braesch, C., Nyffenegger, F. (2019). Analyzing BIM topics and clusters through ten years of scientific publications. *Journal of Information Technology in Construction (ITcon)*, Vol. 24, pg. 273–298.
21. Azhar, S.: Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry, *Leadership and Management in Engineering*, 11(3), 241–252 (2011).
22. Becerik-Gerber, B., Jazizadeh, F., Li, N., Calis, G.: Application Areas and Data Requirements for BIM-Enabled Facilities Management, *J Cons. Eng & Man* 138(3), 431–442 (2012).
23. Eastman, C., Teicholz, P., Sacks, R., Liston, K.: *BIM Handbook: A Guide to Building Info. Modeling For Owners, Managers, Architects, Engineers and Contractors* (2011).
24. Hergunsel, M.F.: *Benefits of Building Information Modeling for Construction Managers and BIM-based scheduling*, Worcester Polytechnic Institute (2011).
25. Dossick, C. S., Anderson, A., Azari, R., Iorio, J., Neff, G., Taylor, J.E.: Messy Talk in Virtual Teams: Achieving Knowledge Synthesis through Shared Visualizations. *Journal of Management in Engineering* 31(1) (2015).
26. Yalcinkaya, M., Singh, V.: Exploring the use of Gestalt’s principles in improving the visualization, user experience and comprehension of COBie data extension, *Engineering, Const. and Arch. Management*, 26(6), 1024–1046 (2019).

27. Kirsh, D. (2010). Thinking with external representations, *AI & Society*, 25(4), 441–454.
28. Schön, D.A.: *The Reflective Practitioner: How Professionals Think in Action*, NY (1983).
29. Russell, D.M., Stefik, M.J., Pirolli, P., Card, S.K.: The cost structure of sensemaking, in *ACM/IFIPS InterCHI'3 Conf. on Hum Factors in Software*. ACM: NY. p. 269–276 (1993).
30. Stalnaker, R.: Common ground. *Linguistics and Philosophy* 25(5-6) 701–721 (2002).
31. Pauwels, P. Zhang, S., Lee, Y.-C. Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, 73, 145-165 (2016).
32. Waller R.: What makes a good document? The criteria we use. From the Simplification centre. The University of Reading (2011).
33. Forward, A., Lethbridge, T.C.: The Relevance of Software Documentation, Tools and Technologies: A Survey, *Proc. ACM Symp. Docum'n Eng.*, ACM Press, pp. 26–33 (2002).
34. Lethbridge, T.C.; Singer, J; and Forward, A. (2003) How software engineers use documentation: The state of the practice. *IEEE Software*, 20(6), 35–39.
35. BuildingSMART. Model View Definition Summary. Available at: <http://www.buildingsmarttech.org/specifications/ifc-view-definition> [Accessed April 12, 2019].
36. Singh, V., Gu, N., Wang, X.: A theoretical framework for BIM-based multi-disciplinary collaboration platform, *Automation in Construction*, 20(2), 134-144 (2011).
37. Pretorius, C.: Exploring procedural decision support systems for wicked problem resolution. *South African Computer Journal*, 29(1), 191-219 (2017).
38. DeSanctis, G., Gallupe, R.B.: A foundation for the study of group decision support systems, *Management Science*, Vol 33 No 5, pp. 589–609 (1987).
39. Sprague, R. H.: A Framework for the Development of Decision Support Systems," *MIS Quarterly* 4(4), 1-26 (1980).
40. East, E.W., Nisbet, N., Liebich, T. Facility management handover model view, *Journal of Computing in Civil Engineering*, 27(1), pp.61–67 (2012).
41. Kuiper, L., Holzer, D.: Rethinking the contractual context for building information modeling in the Australian built environment industry. *Aust. J. of Cons. Eco. & Build.* (2013).
42. Singh, V., Gu, N. Towards an integrated generative design framework, *Design Studies*, 33 (2), 185-207 (2012).
43. Oxman, R.: Theory and design in the first digital age. *Design Studies*, 27(3), 229-265 (2006).
44. Papazoglou, M., Georgakopoulos, D.: Service-Oriented Computing, *Communications of the ACM*, 46(10):25–28 (2003).
45. Love, P.E.D., Tse, R.Y.C., Holt, G.D. and Porverbs, D.G. (2002). Transaction costs, learning, and alliances, *Journal of Construction Research* 3(2).
46. Björk, B.C., Laakso, M.: CAD standardisation in the construction industry—A process view, *Automation in Construction*, 19(4), 398–406 (2010).
47. Laakso, M., Kiviniemi, A.: A review of IFC standardization—interoperability through complementary development approaches. *Proc's of the CIB W78-W102*, pp.26–28 (2011).
48. Shin, D.H., Kim, H., Hwang, J. Standardization revisited: A critical literature review on standards and innovation, *Computer Standards and Interfaces*, 38, 152-157 (2015).
49. Hanseth, O., Monteiro, E., Hatling, M.: *Developing Information Infrastructure: The Tension Between Standardization and Flexibility*. *Sc., Tech., & Hum Values*, 21(4), 407-426 (1996).
50. Park, S.: Standardization and Network Externalities. *Advanced Topics in Information Technology Standards and Standardization Research* 1(1), 251 (2005).
51. Söderström, E.: Formulating a general standards life cycle. In *Advanced Information Systems Engineering*. Springer, pp. 263–275 (2004).
52. Xie, Z., Hall, J., McCarthy, I.P., Skitmore, M., Shen, L.: Standardization efforts: The relationship between knowledge dimensions, search processes and innovation outcomes, *Technovation*, 48–49, Pages 69-78 (2016).

53. Sosa, M. E., Eppinger, S. D., Rowles, C. M.: Identifying modular and integrative systems and their impact on design team interactions, *Jo of Mech Design*, 125(6), 240–252 (2003).
54. Cragil, C.F.: Information technology standardization: Theory, process, and organization. Demian, P. and Walters, D. (2013). The advantages of information management through building information modelling. *Construction Management and Economics*, 1–13 (1989).
55. De-Vries, H.J.: IT standards typology, *Adv. topics in IT standards & standardization research*, 1, 1–26 (2006).
56. Demian, P., Walters, D. The advantages of information management through building information modelling. *Construction Management and Economics*, 1–13, (2013).
57. Deshpande, A., Azhar, S., Amireddy, S.: A framework for a BIM-based knowledge management system, *Procedia Engineering*, 85, 113-122 (2014).
58. Holzer, D.: BIM and Parametric Design in Academia and Practice: The Changing Context of Knowledge Acquisition and Application in the Digital Age. *Int Jo Arch. Comp*, 13(1), 65–82 (2015).
59. Meadati, P and Irizarr, J (2010), BIM – a knowledge repository, Associated Schools of Construction- Annual International Conference, 7-10 April, Massachusetts, USA.
60. Motamedi, A., Hammad, A., Asen, Y. (2014). Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management, *Aut. in Constr.* 43, 73–83.
61. Motawa I, and Almarshad A. (2013) A knowledge-based BIM system for building maintenance, *Automation in Construction* 29, 173–82.
62. Alavi, M., Leidner, D.: Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research Issues, *MIS Quarterly*, 25(1) (2001).
63. Argote, L.: Reflections on two views of managing learning and knowledge in organizations. *Journal of Management Inquiry* 14(1), 43–48 (2005).
64. Choi, S. Y., Lee, H., Yoo. Y. The impact of information technology and transactive memory systems on knowledge sharing, application, and team performance: A field study, *MIS Quarterly*, 34(4), 855–870 (2010).
65. Wegner, D.M.: Transactive memory: A contemporary analysis of the group mind. In *Theories of Group Behavior*. Springer, pp. 185–208 (1987).
66. Nonaka, I. and Takeuchi, H. (1995). *The knowledge-creating company: How Japanese companies create the dynamics of innovation*, Oxford university press.
67. Holmström, J., Singh, V., Främling, K.: BIM as Infrastructure in a Finnish HVAC Actor Network: Enabling Adoption, Reuse, and Recombination over a Building Life Cycle and between Projects, *J. Ma. Eng.*, 10.1061/(ASCE)ME.1943-5479.0000305, A4014006 (2014).
68. Endsley, M.R.: From Here to Autonomy: Lessons Learned From Human–Automation Research. *Human Factors*.59 (2016).
69. Endsley, M.R.: Automation and situation awareness. In R. Parasuraman & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 163-181). Mahwah, NJ: Lawrence Erlbaum. (1996).
70. Parasuraman, R., Sheridan, T., Wickens, C.: Situation Awareness, Mental Workload, and Trust in Automation: Viable, Empirically Supported Cognitive Engineering Constructs. *Journal of Cognitive Engineering and Decision Making*. 2. 140-160 (2008).
71. Singh, V., Holmström, J.: Needs and technology adoption: observation from BIM experience, *Engineering, Construction and Architectural Management*, 22(2), 128-150 (2015).
72. Brown, T.: Design Thinking. *Harvard Business Review*, 86, 84–92 (2008).
73. Wing, J.: Computational thinking, *Communications of the ACM*, 49(3), 33–35 (2006).
74. Senge, P.M. *The Fifth Discipline*. New York: Doubleday (1990).