Beyond e-permitting: Framing the Business Case for Automated Rule Checking in AEC in the Era of Big Data

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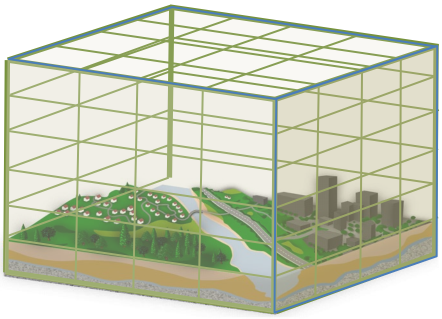

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Executive Summary

This report is the result of a review commissioned by the buildingSMART International Regulatory Room. It explores the emerging future of automated rule checking (ARC). ARC is no longer just a “technical tool” needed to spot or study errors in design or work plans. Increasingly, research and applications of ARC are going beyond “box-ticking” compliance with regulatory rules. ARC is no longer just a cost-saving “software tool”, but a money-making “service or product”. Consequently, instead of the top-down, expert-system-like format, new forms of ARC are semantic-savvy, and are based on (bottom-up) analytics and machine learning approaches. ARC can now be used to automatically generate the analyses and/or services that consultants or contractors deliver. In fact, it can now (partially) be used to generate the design or work plans themselves.

The interest in such types of ARC is a reflection of the growing importance and feasibility of AI (artificial intelligence), not just as an advanced form of sophisticated analysis tools, but as a driver for new business. The ability of using advanced AI approaches in these new types of ARC is a key outcome of the maturity of BIM in the industry. Thanks to IFC (Industry Foundation Classes), we now have a data-rich environment, where machine learning and pattern analysis can help us discover and use rules more effectively.

Companies that master the inclusion, deployment and marketing of ARC capabilities will be more competitive in the new economy. Consequently, the “business value” of ARC is changing. It is poised to be a generator of services/ products not a quality control mechanism. Increasingly, it directly contributes to realizing new segments in the market. This ranges from products for automated analyses (including the automation of designs), to products for customization and delivery of information to customers (analysis-on-demand), to enhancing real-time management of sites and facilities (intelligent buildings).

However, ARC value goes beyond the automation of some technical analyses within a digitized system (making more software more intelligent). More importantly, one of the key values of advanced forms of ARC is its role in organizational transformation. The sophisticated considerations and cultural changes needed to develop and deploy an ARC make it an effective linchpin for enterprise-wide AI initiatives. The expertise gained from implementing advanced ARC can be the best testbed for wider reengineering of business process, automation of workflow, and the deployment of business intelligence within the firm (or a facility). In other words, the sophistication of ARC implementation will propel the re-making of the firm not just its services. It changes the firm as it changes its offerings.

To support better understanding of this new reality, this report aims to frame the business case for ARC, with three main considerations: 1) ARC is a form of machine learning system—it is not limited to an expert system tool; 2) ARC includes checking rule compliance and the generation of rules through data analysis; 3) because of its role in assuring the transformation of enterprises into

the AI-savvy economy, the business case analysis should reflect that. The business case should not be made only based on the interest of a technical team (cost savings through partial automation of some technical processes). Rather, it is to be made to an executive who is considering the customer needs and service offering and, indeed, the future, structure and strategy of the firm.

It is almost impossible to perceive a single/unified model for evaluating the business case or ROI (return on investment) for ARC. Repeated attempts to do so for ARC (indeed BIM itself) have resulted in varying (if not conflicting) results. The reasons may include the fact that ARC efficiency is dependent on the efficiency of BIM deployment itself; and the limited history of ARC deployment in the e-permitting process and otherwise, which limits the availability of data. The reliability of available data is another problem. But, equally important, studies that considered ROI on ARC or BIM have been limited (in most incidents) to conducting case studies, which are typically sensitive to the context of the project or company considered.

It is argued that developing the business case for the AI-enabled ARC may not be feasible at this time. Instead, it could be more effective to establish a framework for building and presenting such cases in a manner that enables future comparisons of these cases. Cross-case analysis will, for sure, be more insightful than any individual case. For that, we need to build/agree on a consistent format for developing future studies.

This study proposes that five dimensions be used in the modelling, analysis and presentation of any future business case for ARC. Each dimension is seen as a complex network of concepts. The first and second networks are, as expected, the list of costs and benefits considered. The third is the methodology used in developing the study. Other than case study approach, new methods should and are being investigated. For example, the use of value networks can help us represent the complexity of benefits; support presenting the case in a “business” not a technical language (not simplified dollar values); and enhance capturing the impacts on each stakeholder. The third dimension is the context (boundary conditions) of the business case. This covers the nature of ARC being analysed, the domain of application, the relationship to BIM implementation maturity, etc. The neglect of this dimension is, partially, the reason for conflicts between previous studies conducted in this domain. To this end, the fifth network relates to profiling the stakeholders targeted or considered in the case. Capturing a universal value proposition (and ROI) for all stakeholders, in addition to being context-dependent, is a complex process. Isolating the analysis to one (or a subset) of stakeholders can simplify the analysis and better make the “case” to such stakeholder.

bSI can enrich R&D in this domain through encouraging the development and use of consistent frameworks for representing future studies. Hopefully, this will provide a multi-perspective platform for understanding of the value of ARC; and allow for more efficient comparative analyses of the determinants of ROI.

1. INTRODUCTION

This report aims at framing the development of business cases for automated rule checking within a BIM (building information modelling) environment. Automated rule checking in the Architectural Engineering, Construction industry (AEC) is a means to check on the satisfaction of/or compliance to a rule. Generically, automated rule checking (ARC) refers to the use of a computer program to assess a design based on product configuration through encoding rules, and thus allowing facility models to be evaluated against these machine-based rules (Eastman et al. 2009; Bormann et al., 2009). Typically, the objective for using ARC is speed, error reduction, and reliability (making sure all rules have been reviewed). Consequently, the most common application of ARC has been in the area of regulation compliance. Using IFC (industry foundation classes) attributes and a "rule model", a set of heuristics can be implemented to check for the satisfaction of code or regulation. Of course, realizing full automation in rule checking is, most probably, infeasible in the foreseeable future. Rules are subjective and, in many cases, can conflict. With the increased orientation towards performance-based regulations, the ambiguity and the need for human interpretation will only increase. For that, automated rule checking in this report refers to, essentially, a partial and a semi-automated system.

ARC applications, especially lately, have expanded beyond regulation checking. IFC introduced parametric modelling and data interoperability to AEC. With such formalized, data-rich environment, researchers have implemented several ARCs to study and evaluate additional aspects of AEC work. In fact, within the scope of this report, the domains of application of ARC span four major fields of study, as follows (see Appendix A for detailed review):

> Traditionally, ARC was limited to a simplified set of rules (driven by an expert), to check for regulatory compliance. ARC can, now, use advanced AI tools (machine learning and data analytics) to extract the rules themselves and apply them to new applications. This includes automated technical and project management analyses; real-time management of intelligent buildings; and even automated generation of designs themselves.

1. <u>Code-compliance</u>: the traditional checking of public regulations to (partially) secure permits.
2. <u>Automating the consideration of best practices and knowledge in work activities</u>: many researchers used a set of "rule models" to embed some of AEC knowledge within a BIM environment. The aim is to check or coordinate the implementation of rules that captures some of the relevant knowledge to help evaluate or enhance technical analyses. These evaluations are applied to a wide range of issues, such as programmatic requirements, model correctness; or analysis of key design and construction issues, such as safety, energy, accessibility, constructability, maintenance, and facility management.
3. <u>Smart facilities and data analytics</u>: traditionally, BIM integration with IoT (Internet of things) was focused on the use of BIM for visualizing where sensors/actuator are. New trends, however, are trying to combine IoT real-

time data with the geometric and product attributes of the facility (from BIM) to conduct rule-based, real-time analyses. For example, assessing timely compliance with rules for air quality or energy usage levels based on occupancy counts, energy consumption levels (or air quality indicators) and space (zone/room) size and features. Interactively, these can be communicated to facility managers or occupants themselves.

4. Design automation: recent work has included using machine learning and iterative algorithms to develop design alternatives (especially in relation to optimal layout). In all previous categories, BIM is used as a source of data for extracting facility or design attributes. Here, developing the design (and examining its possible alternatives) is the target of the analysis and rule application.

The objective of this report is to frame not create the business case for advanced ARC systems. This is because the new forms of ARC are still evolving; and their value is context-dependent based on the project and stakeholder attributes. Creating this base framework can make future business cases consistent and allow for more informative comparison of such cases.

This report aims to collate means to study the business case for ARC in non-code-compliance applications and for non-government stakeholders. The aim is not to develop the structure of a universal business case, let alone finding the dollar values of costs or benefits. Rather, the aim is to develop a framework for the main components that an assessment of ROI for ARC should include. Considering the changes in ARC environment - particularly, the new applications, the new stakeholder profiles and the potential for artificial intelligence (AI) exploitation in AEC, what are the main elements that can be considered in building the business case? Such a framework can act as roadmap and a simplified ontology for the components and methods for developing future business cases. Repeated use of such framework creates consistency in representing cases. This provides means for linking cases and better comparing them; and, possibly, the ability to implement machine learning tools to find patterns (in costs and benefits, for example).

Below is a brief discussion on the forces of changes that are creating opportunities for new horizons in ARC. This is followed by a description of the scope and objectives of this study, which is designed to be 1) aware of the existing opportunities and upcoming changes, and 2) support a sense of consistency in the development of such future cases. This is followed by the general outline of the proposed framework. The framework is intentionally not deep in terms of details. Fuzziness at this stage is needed to encourage varying ideas and debates. Two appendices are included in this report. The first provides a background about the long history of ARC in code compliance (typically within an e-permitting scenario). Then, a summary of advancement of ARC-like work in the other scenarios is presented. The second appendix presents a synthesis of work done on establishing the business case for BIM and BIM-based ARC.

Winds of change

IFC transformed the industry by creating a data-rich environment. ARC can take the industry to the next level in machine learning and data analytics.

IFC role in BIM was to promote formalized modelling and exchange of data (creating an interoperable data platform). With such data-rich environment, arguably, ARC true role is not in “modelling” and checking on regulations. It can be a powerful tool to promote moving the industry to effective and sustained use of machine learning and analytics. This makes ARC an essential part of the reengineering of firm’s business model and its survival in the new economy. The industry is notorious for its lack of data culture and data itself. The only possible exceptions are the design data and real-time data. There is a rich amount of data generated and recorded in the BIM model of every new design. And through the advancing use of IoT, a wealth of facility data will be easily generated. Using this data, ARC that is based on advanced data analytics and machine learning systems can help realize a transformational boost to AI applications in the industry. In other words, IFC helped create data repositories—ARC can be the tool to applying AI on such data. In this realm, ARC is not about an expert developing rules to be checked. Rather, learning from the data to study patterns and extract the rules themselves. We can start thinking of using machine learning for extracting rules bottom-up through data analytics and pattern detection—instead of top-down by experts. The results of such implementations is a transformational change to AEC practices from automated analyses, to computer-generated designs.

The value proposition of such AI-enabled ARC spans three dimensions. First, on the technical dimension, professionals will be able to conduct more advanced analysis and use the analytics to learn from data. Second, ARC will open new markets and enhance company competitiveness. Finally, ARC can be one of the most effective steps (a linchpin) for organizational transformation and wider adoption of AI.

<u>The Business of AI</u>: The first major impact of advanced ARC is related to the business offerings of AEC companies. Traditionally, the value of ARC was limited to its technical contributions: increased efficiency and reliability of design (and construction) tasks. The main advantages of ARC were in capturing errors, reducing review time, enhancing design, and increasing consistency. However, business executives are starting to pay attention to the role of ARC in meeting and creating market demands for AI-savvy applications. As a case in point, IBI, a leading Canadian consulting firm has adopted a significant and bold strategic change to pivot as a technology firm. They will still offer the same consulting services in planning, design, and project management in buildings and infrastructure. However, this will be delivered, mainly, through an advanced platform of analysis systems and software. At the core of this re-pivot is investments in automation, research, and incubating innovation. Implementing elements of ARC can be the key to realize some of these goals. In short, ARC value is now viewed within the realm of its impacts on organizational transformation—not just its impact on technical efficiencies for some tasks.

Companies and investors (such as IBI) foresee a market need for new services that rely on data management, automated analyses and real-time control. In this regard, ARC-based systems become the core business offerings. In this new world, ARC-based systems realize the business value—not just add to it. With the expansion of data-driven possibilities in AEC, increasingly, ARC is needed for a multitude of tasks and by new stakeholders. Key among these are designers and contractors. However, their needs go beyond regulatory compliance to the realm of design optimization and, indeed, its development. Facility operators are also starting to pay attention to the value of ARC for supporting optimal operations of facilities and for engaging occupants and increasing their comfort. The most impactful beneficiaries of ARC, however, could be big owners/developers. Typically, designers and contractors had to make the case to the owners that investing in BIM is good for the bottom line of the project—with benefits potentially transferred to the owner in the form of reliability and efficiency of design and construction work. In the case of implementing ARC, owners (especially large developers) can realize direct significant benefits from assuring code compliance as it will reduce permitting time and will reduce errors and any associated re-work, claims and change orders. A more significant shift to promoting the value of ARC is the owner/developer interest in smart facilities. Such owners are savvy and recognize the importance of BIM as a communication platform. Many are also aware that, by using ARC systems, BIM can be the basis for an AI platform, which is predicated on integrating algorithmic analysis with BIM data. In other words, much like the Internet or social media, BIM is not just a place for "storing" data, it becomes a fertile ground for data analytics and business intelligence.

AI-enabled ARC is not only a powerful tool for technical analysis, it creates new business opportunities and can help re-make the organizational culture

Testbed for organizational change: Going through the development and implementation of AI-enabled ARC requires cultural changes that, if implemented effectively, can act as a testbed for overall company transformation. The industry is poised for major changes. This due to factors that range from increased demands for sustainability, to the advent of smart facility and artificial intelligence to, possibly the most important factor, the growing role of customers in decision making and co-creation of knowledge. Innovation and effective change management abilities are keys to the competitiveness of developers and contractors in this emerging market. Finding a right approach to transform the company to these new realities is crucial to its survival.

The scope of AI-enabled ARC cannot be implemented as just a "technical exercise". The whole (business model and structure of the) company must change to adapt to that. Hence, taking on the challenge of developing and implementing ARC (beyond regulatory compliance needs) is one of the best means to induce the required transformation. ARC essential value here goes beyond re-making the services into the re-making of the company. In other words, because AI-enabled ARC is a gateway to data analytics, the challenges and changes required to implement it provide the best means to test and boost organizational abilities and capabilities for change—which are inevitable in today's economy.

In summary, ARC has value in technical and business aspects of the AEC work. Its technical uses are evolving beyond code-compliance. However, because of its role in promoting AI, new benefits and beneficiaries are evolving fast. These transformative trends are changing the value proposition of ARC. Its traditional role as means to optimize a design or embed best practices in a design can be trumped by its potential for being the linchpin for AI in the industry.

2. SCOPE & OBJECTIVES

Adoption of BIM (certainly its prolific spread lately) was based on both economic (business) and technical reasons. As we progress in developing the models and tools of ARC, it is important to pay added attention to studying the market-side of ROI of ARC. This is very important given that there has been an extensive focus on the "technical" aspects of the ROI in the "era" of ARC for regulation compliance.

Much like assessing the ROI of BIM, the task of doing the same for ARC will remain very illusive because of the subjectivity of cost/benefit factors, and the impact of context (nature of design and stakeholders) on the valuation. Furthermore, calculating the ROI of ARC faces the added challenge of discerning the value/contribution of ARC from the overall contribution of BIM usage itself (is the calculated value/cost related to ARC or BIM itself). Even more, how to address the dependency of ARC feasibility and efficiency on the level of BIM maturity (at project or organizational levels).

Therefore, one of the most effective means to support better understanding of the ROI of ARC is to keep collecting and analysing data and cases. To help create some consistency in developing these cases, this report presents a framework (conceptual ontology) that will allow interested parties (possibly bSI) to create an "interoperable" repository of cases about the ROI of ARC. With time, the accumulation of consistent case data will enable formalized analytics. In other words, the proposed framework is an "IFC" for ARC business case attributes—the more we use it, the more we enhance the framework itself, the more we collect data more reliability, and the more we can conduct objective analysis that can overcome the above limitations.

The new values of ARC

BIM-based automated code checking has been traditionally considered in the context of e-permitting. This possibly is related to the push for e-government and the increasing demand for efficiency in the permitting process, which has been shown to have a major impact on development or even economic activities on a regional level. The complexity of establishing an e-permit system, and its reliance on the level of maturity of BIM within a jurisdiction, makes it very hard to quantify the value of ARC—indeed demarcating the divide between ARC costs and benefits from those of the overall e-permitting process is very hard.

To explore wider horizons for the applications of ARC, the types of rules considered in this report include this expanded view:

- A code by a large or specialized owner: large conglomerates can establish additional code and rules for their facility design and construction. Presenting such code in a BIM-compliant ARC will help designers quickly learn and get familiar with such specialized code.
- Optional codes & certification: with the increased interest in green and energy-efficient practices, rules and guidelines for relevant programs in this field (such as LEED) are akin to code.
- Exploratory codes: in many cases, national regulators put proposed code changes to the test or for input by practitioners. Using ARC can help reach out to more practitioners for testing and for examining the proposed code in diversified contexts.

The nature of ARC approach/technology is also expanding, including, for example, the following options:

1. An ARC can be a rule-based system (as is the case with the overwhelming number of developed ARCs). It can also be in the form of MVD (model view development). A typical ARC checks against technical rules. An MVD checks for data availability, quality and consistency - all of which are essential to compliant submission of permits or the applicability of a generic ARC to a design. Closely related to this is work on product data databases or query languages. These are essential for extracting the right/required data for applying an ARC.
2. An ARC can be developed based on data extracted from an IFC file or through semantic analyses of documents. The latter attempts to integrate specifications (and other documents and text sources) as a source of data and as a target for rule-checking.

> It is time that code agencies issue their regulations in code

To this end, it is obvious that the most optimal approach for making automated code checking a reality and done with the best ROI is when regulatory agencies develop code in the form of an equation, algorithm or heuristics. Digitizing codes at the inception stage is not only helpful to the industry, it is also beneficial to the regulatory agencies. By embracing digitized (and BIM-compliant) code, regulators can benefit from the data collected about the usage and problem patterns. This can help in evaluating and refining new code. Such task is increasingly becoming important given the complexity of scope and depth of requirements in modern codes. It can also make the deployment of such code faster. In fact, it will be very challenging to realize a smart city with automated cars or interactive facilities with a non-digitized code. For example, it will be essential to assure the compliance of an automated vehicle operated by a private sector agency with code in real-time.

There has been an extensive body of work in relation to the use of ARC in the e-permitting (regulatory approval) context. This has meant that the main benefits of ARC were limited to technical aspects—for example:

- The role of automated code checking in reducing/capturing design errors: discovering these after design approval can typically result in delays and, if discovered during construction, rework.
- The role of automated code checking in reducing premiums for professional insurance incurred by design firms.

While these benefits are reviewed here, this report is focused on analysing the additional market and enterprise-oriented benefits—for example:

1. Process efficiency: the focus of previous work has always emphasised the prevention of errors (to reduce rework). With the increased abilities of ARC and the growing complexity of the design/planning processes, the role of automated identification of errors in enhancing the overall efficiency of the design process is becoming significant—especially the management of changes and review tasks. Because of the multidisciplinary nature of design teams, not all members of the team will be fully versed in the code components in all disciplines. An automated code checking system will help a team member avoid violating a code in a discipline that they are not experts in. Furthermore, because of the complexity of code in many disciplines, a review is always conducted by a senior staff member. Automated code checking can reduce the time of this task by helping junior designers avoid some mistakes.
2. Education: by allowing junior designers to study errors, advanced ARC can help them discover and understand areas of code violations. Such self-directed learning is very valuable. It is, however, not a replacement for other training means.
3. Innovation: in many cases, the burdensome nature of analysing code compliance can deter designers from experimenting with alternative or risky ideas. The speed of evaluating alternatives using ARC can encourage them to develop and examine more options.
4. Design automation: a future for partial automation of some elements of project design is certainly possible. It is, however, infeasible without automated code checking.
5. Data analytics and pattern discovery: the automation of code checking introduces this task to the realm of digitized processes. This will allow users to collect data about violations, and, possibly, the reasons for such violations or products or design schemes that can increase the levels of code violations.

Scope of the framework

One of the key points of this framework is to explore additional methods of analysis. Case studies have dominated research work in the domain. The typical approach for these cases focused on “crunching” the savings due to early (and effective) identification of design errors, hence reducing chances for re-work. We should diversify the analysis approaches through including econometric and other business-oriented methods. This is because, increasingly, the value of ARC is related to the automation of work processes and enhancing the firm’s offerings and capabilities in AI-based products and services. Additionally, better capture and analysis of boundary conditions of business cases should be integrated in the analysis: what type of projects, firms, and situations does the study apply to? Finally, stakeholders should be better profiled as part of any future business case study: to whom is the ROI calculated?

To this end, the new cost/benefits that are emphasized in this study are driven by a set of business values/trends (in contrast to the traditional "technical" objectives used in previous studies). Furthermore, while the core target of this analysis is the design stage, it is equally cognizant of the role of ARC in planning, construction and operations.

1. (certified) services for the savvy owner: Owners are now aware of the importance of design quality and its role in reducing construction problems and enhancing the overall life cycle management and costs. So, they are willing to pay more to (or have more business with) savvy consultants, contractors and operators who can offer reliable assurances and justifications of the quality of their work. In other words, there is an increasing potential that ARC-rich services can be sold or, at least, enhance the chances of selling other design/project management services.
2. Overhead of increasingly complex processes: Work process are becoming more complex, with increasingly more subjective issues to consider. This necessitated more reviews and increased (back and forth) communications and discussions. Simply, the overhead of work processes in the industry has increased. This highlights ARC role in increasing the efficiencies of design and construction, even if it does not catch errors. ARC role in saving more time for more staff members is important as its role in reducing re-work.
3. Adaptability: the pace of changes in rules (for code and otherwise) in the industry is increasing. Having an ARC in place will make testing and implementing new rules much faster. It will also make the analyses of the value/impact of such new rules easier.
4. Training: With the higher turnover rates and the increasingly multidisciplinary nature of work and analyses in the industry, ARC can be very valuable in training new staff members. They can try many options and evaluate them and check on rules before escalating their proposed analyses to the next level.
5. Linchpin for AI: Embarking on building and implementing an ARC will require sophisticated analyses. The promotion of such advanced system pushes almost every department in a firm to use and build competency in artificial intelligence tools; and embrace process automation paradigms. Further, AEC firms now have an extensive repository of (IFC and BIM) data. A well-developed ARC system can make the use of machine learning tools within this data-rich environment more feasible. In other words, the role of ARC in promoting AI usage could be more important than its money savings in error catching and reduction of overhead.
6. Ready for the future: Beyond the role of ARC in realizing a company-wide AI platform. AEC is poised for substantial change in all fronts. Taking on the transformational challenges (and sophistication) of implementing ARC is one way for testing and enhancing organizational capacity for innovation,

resilience and change management—all will be crucial to the survival and competitiveness of firms in the future.

Finally, this is an exploratory analysis. Further studies and development are needed. bSI should support efforts for understanding ROI of ARC through the following means. First, promote the re-use of a common assessment framework to create a consistent, interoperable repository of ROI data and cases. Second, establish/promote collaboration with experts from other industries (that have implemented elements of ARC) to learn from and work on implementing/ benchmarking different analysis methods.

3. THE PROPOSED FRAMEWORK

There is a strong linkage and similarities between the value and the costs of the adoption of BIM and those related to the use of BIM-based ARC. This, on the one hand, can help us benchmark studies that considered the evaluation of ROI of BIM. On the other hand, if we limit ARC scope to regulation compliance or error finding, it is typically very hard to discern specifically the value of ARC within an organization that uses BIM. Adoption of BIM enhances collaboration and information flows and enables better visualization and analyses—all of which will help in enhancing design and avoid errors (the typical benefits of ARC). In other words, ARC mainly formalizes what is done manually by using BIM. For most researchers, this meant that, effectively, the core advantages of ARC can be assumed to be: not just catching errors, but doing so faster and more reliably.

However, one of the main claims of this study is that ARC should be viewed with a wider scope of applications and values. The two appendices discuss new trends in the assessment of ROI both for BIM and ARC that are influenced by business thinking. This is because, lately, business value of BIM (and ARC) are becoming apparent and, possibly, equally important to their technical value. In general, these new business values revolve around two main features: 1) for firms with traditional business processes, BIM and ARC increase efficiency; 2) for firms aspiring to automate business process, BIM and ARC can provide a significant boost to their work in this regard. In other words, BIM and ARC enhance process efficiency and make automating them much easier.

In addition to the typical problem of quantifying and discerning costs and savings, analysis of relevant research work shows three major issues in establishing the ROI and the business case for ARC:

1. The quality of the design itself: It is important to note here that using an ARC cannot prevent re-work or change orders. This is not only because ARC will never be able to prevent mistakes or capture all errors but because a multitude of factors contribute to these cost overruns. However, ARC has value beyond code compliance checking. ARC can make the design better in other ways. It can be used as a guide: search and filter components of a design and suggest or prioritize areas where the designer or contractor should pay more attention. In other words, it can act as a support for enhancing the overall quality assurance of the design, and, to an extent, advice the designer of areas of potential problems or opportunities for enhancement. For example, if, as some case studies have suggested, steel and concrete members are the most prone elements for high-cost mistakes, it is possible that an ARC system can be created to pinpoint the most important of these for the designer to review or discuss in more depth with the contractor.
2. The design and design review processes: the increasing complexity of designs is making the process long and iterative. An ARC can help in making the overall design process shorter by advising designers and finding issues and errors faster. The process of design review is typically conducted by senior members of the design team, with typically higher salary rates. If

it becomes more complex and/or lengthy, the overall efficiency of the process will suffer (and costs of design will increase). Again, this type of "business" consideration is gaining more interest lately.

3. Overlap with BIM ROI: is the value generated due to (efficient discovery of errors by) ARC or due to (the coordination efficiency due to use of) BIM? The very use of BIM (even at the basic level: visualization) plays a major role in enhancing the "design" through avoiding the causes of mistakes. It also plays major role in enhancing the efficiency of the "design process". So, it is hard to discern the contribution of BIM and that of ARC to savings (if we can calculate them).

One key agreement between researchers is that when there is uncertainty or complexity, management efficiency and contractor engagement (typically in a turnkey contract) will lead to better handling of rework causes and enhanced capture and analysis of data (Love et al. 2011; Love et al. 2012). Again, the interrelationships and complexity of stakeholders' networks and their roles is obviously an important aspect for any analysis of ROI on ARC.

To this end, there is a need to diversify the methods used for assessing the cost and benefits of BIM and ARC. Modeling ROI attributes based on network theory to capture the complexity of issues and the complexity of stakeholders' relations can be a very helpful advancement in this regard. Such approach can support more effective analysis—see for example, the use of social network analysis in this regard by Hattab and Hamzeh (2015). Formalizing the issues and/or the interrelationships between stakeholders in the form of a network is a significant step that can enable sustained and cross-case analysis. The structured nature of networks can increase the chances for using machine learning to capture trends: network analysis and pattern detection as the means to find and examine value exchanges.

A more significant change is to shift from crunching the dollar savings. It would be helpful to focus on identifying, modelling and (possibly) quantifying business and marketing values. This is because, increasingly, the decision making in BIM adoption and the use of ARC is seen as part of the business not the technical realm of the organization.

The proposed framework includes five dimensions—each is seen as a network of concepts. The framework is the network of networks—see Figure 1. At the core are the networks of costs and benefits. They are linked to three other networks: methodology, boundary conditions, and stakeholders. It is important that each new business case clearly stipulates the methodology and approach used. This includes clarification about the analysis approach, its steps and its relevance to the study; the nature and size of data; the models and assumptions made about costs and benefits; and the applicability and re-use of the proposed case. The boundary conditions dimension is meant to capture the context of the proposed case. This include the type of projects considered, the nature of ARC investigated; the extent and maturity level of BIM within user organizations and within the case project itself. The final dimension is related to stakeholders considered. This framework encourages developers of business cases to clearly consider the values and costs from the perspective of each stakeholder.

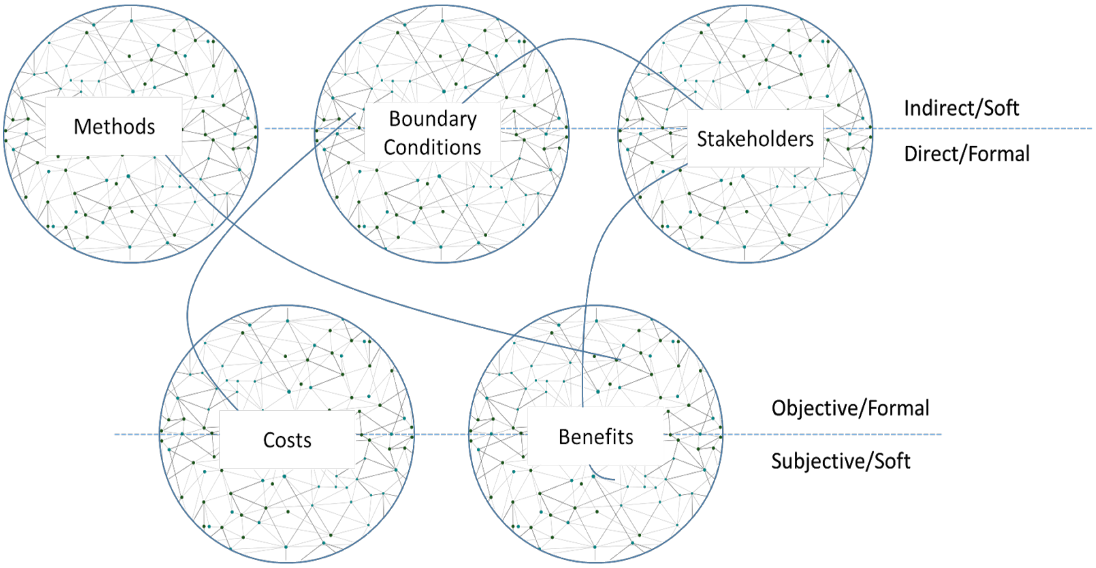

Figure 1: The networks of ARC business case analysis

Benchmarks and key studies

This framework was influenced by the analyses of the studies discussed in the appendices. The conceptual approaches of the following ones were significant in the thinking behind the proposed model

- Won, J., & Lee, G. (2016). How to tell if a BIM project is successful: A goal-driven approach. Automation in Construction, 69, 34-43.
- Fortineau, V., Paviot, T., & Lamouri, S. (2019). Automated business rules and requirements to enrich product-centric information. Computers in Industry, 104, 22-33.
- Lee, H. W., Oh, H., Kim, Y., & Choi, K. (2015). Quantitative analysis of warnings in building information modelling (BIM). Automation in Construction, 51, 23-31.
- Zheng, X., Lu, Y., Li, Y., Le, Y., & Xiao, J. (2019). Quantifying and visualizing value exchanges in building information modelling (BIM) projects. Automation in Construction, 99, 91-108.

However, two key studies have had direct (re)usage in the elements of the framework

- Love, P. E., Matthews, J., Simpson, I., Hill, A., & Olatunji, O. A. (2014). A benefits realization management building information modelling framework for asset owners. Automation in construction, 37, 1-10.
- Oesterreich, T. D., & Teuteberg, F. (2018). Looking at the big picture of IS investment appraisal through the lens of systems theory: A System Dynamics approach for understanding the economic impact of BIM. Computers in Industry, 99, 262-281.

The first study considered a multitude of perspectives for what creates a value and methods for assessing the benefits, beyond the dollar crunching approaches typically used in this domain. The proposed approaches are also influenced by business thinking. Finally, the study considers the operational and asset management phase, which is not typically covered by other studies. The study lists the following approaches and issues directly related to the scoping and analysis of ROI:

- Active Benefits Management (ABM): Establishes ABM in the context of business change; identifies business change needed to address strategy; and establishes relationship between change and benefits.
- Cranfield Process Model: Potential benefits are identified, a plan devised for their realization, and the plan is executed and results reviewed and evaluated. Constant diagnose of why some projects are successful in delivering benefits through monitoring and feedback.
- Benefits Realization Approach (BRA): Shift from a sole focus on project management to business program management, disciplined portfolio management, and governance. Success of BRA depends on measurement, accountability and proactive change management.
- Process of Active Benefits Realization: Process of managing information systems development through a continuous process of evaluation (i.e. iterative process of evaluation) At the core are active participation of stakeholders, and direct and continuous focus on benefits.
- Benefits Management Life Cycle: Planning alignment between IT and business strategy; Systems analysis; Identifying and managing change; On-going review of benefits.
- Benefits Realization (Best Practice): Continuous process that focuses on capabilities and learning; benefits planning, delivery and review.
- Benefits Breakdown Hierarchy: Management and monitoring of benefits during the initiation and execution; mapping value path relationship between benefit and project forms a hierarchical benefits structure; and creation of capabilities to deliver projects.
- Benefits Realization Management: Identifying and engaging stakeholders through establishment of vision and objectives, management of expectations and using measures to track performance.
- Benefits Realization Capability Model: Capability is enacted through and defined by the realization of competencies. Competencies are enacted through and defined by practices which are underpinned by knowledge, skills, experience and behaviours.

The second study is an ROI for BIM developed by accountants! It is written in the manner a business executive would be expecting for a business case. It has comprehensive coverage of costs. Furthermore, the authors considered and simulated the dynamics between cost and benefit factors, showcasing clearly their interrelationships. They provided the following comprehensive and business-savvy list of costs (C) and benefit (B) categories:

Personnel and labour

- <u>Skills and training (C/B)</u>: BIM user trainings result in additional costs, but also in a higher skilled workforce. BIM enables a higher training efficiency.

- Injuries and accidents (B): Higher skills due to an enhanced training and overall decrease of injuries and accidents.
- Employee satisfaction (B): The increase in skills and the decrease in injuries and accidents can help to improve the working conditions. Employee satisfaction is expected to increase and staff turnover is expected to decrease.
- Capacity and productivity (C/B): Productivity is expected to decrease due to disruptions of the business activities in the early stages and additional personnel capacity maybe required for the implementation and operation of BIM. BIM helps to reduce errors and defects and thus the required staff capacity for rework. This results in a higher productivity.
- Workforce (B): Due to the lower staff turnover, workforce remains stable. Recruitment costs are expected to decrease.
- Labour costs (C/B): higher skilled employees normally demand a higher salary.

Customer and market

- Delivery and output quality (B): The overall reduction of project time and the decrease of errors and defects are expected to result in an improved delivery and output quality.
- Customers (B): In-time delivery and improved output quality positively influence customer satisfaction, which in turn leads to an increased recommendation rate. As a result, the customer base is expected to grow.
- Contracts and revenue (B): More satisfied customers and a higher customer base result in a higher number of contract orders.
- Reputation (B): Alongside with a higher customer and employee satisfaction, the improved environmental performance of the organisation is expected to result in a better corporate image and reputation.
- Market position (B): Given the growth in revenue, which is resulting from the improved order situation and the higher productivity, the market position and share are expected to increase.

Finance and accounting

- Revenue and production costs (C/B): BIM requires high investment costs (e.g. organisational costs, human costs, initial and ongoing costs). On the other hand, BIM is expected to increase revenue and reduce costs (e.g. indirect costs like labour costs, material and equipment costs and overhead costs like recruitment costs).
- Assets and depreciation (C): Depreciable investments of BIM such as hardware and software costs are expansion investments to the company's assets, which results in a certain amount of depreciation in each period of the investment's economic lifetime.

- Debt (C): The financing of acquisition costs can usually not be accomplished through external funding, which increases the overall debt account.
- Cashflow (C/B): The incomes and outcomes of the company result in a certain amount of in- and out-payment in each period.
- Taxes (B): The tax effect of the BIM investment depends on the amount resulting from the overall cost reduction and increased revenue.
- Profit (B): at company level, BIM will increase profit.

4. Concept Network I: Costs

The elements suggested below are almost direct re-listing of those suggested by Oesterreich and Teuteberg. They almost match cost items that are to be expected by a business executive in a technology business case.

It is important to mention here few points listed by the authors: “the quantification of direct costs is less complicated than the quantification of social and organisational costs which are mostly intangible in nature [34, 39]. Double counting often occurs in complex analyses where the same costs can be included in different positions. It is also possible that significant costs are omitted by mistake. Hidden costs occur when the share of overhead costs is too small, or the inclusion of personnel or other resources is incomplete. Another cost-accounting problem are spill overs, which lead to secondary financial effects [40]. At this point it is not useful to provide average costs, as the total investment costs of BIM are heavily depending on the question whether the investment is simply the process of buying software and hardware and training users or whether it comprises a more comprehensive process of change [43].”

The authors also state “We base the structure of the BIM cost framework on the cost taxonomy of Irani et al. [39], as it enables us to define costs of BIM investments as socio-technical system costs and thus to take into ac- count the wide range of social and organisational aspects associated with BIM. According to socio-technical systems theory, every socio- technical system consists of a technical subsystem that comprises all processes, tasks and technology components required for running the system, as well as a social subsystem, that is concerned with employees and their attitudes, knowledge, skills, values and interrelationships [41]. It is assumed that the two subsystems are correlatively interacting [41] and that a joint focus on both subsystems is fundamental to identify hidden costs of IS investments [42].”[1]

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[1] [34] P.E.D. Love, I. Simpson, A. Hill, C. Standing, From justification to evaluation: building information modeling for asset owners, Autom. Constr. 35 (2013) 208–216,
[39] Z. Irani, A. Ghoneim, P.E.D. Love, Evaluating cost taxonomies for information systems management, Eur. J. Oper. Res. 173 (2006) 1103–1122,
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[41] J.S. Bostrom, M.I.S. Problems, Failures, A socio-technical perspective, part II: the application of socio-technical theory, MIS Q. 1 (1977) 11–28.
[42] S.D. Ryan, D.A. Harrison, Considering social subsystem costs and benefits in in- formation technology investment decisions: a view from the field on anticipated payoffs, J. Manag. Inf. Syst. 16 (2000) 11–40.
[43] J. Hardi, S. Pittard, If BIM is the solution what is the problem? A review of the benefits, challenges and key drivers in BIM implementation within the UK con- struction industry, J. Build. Surv. Apprais. Valuat. 3 (2015) 366–373.,

Indirect costs

Organisational costs

- Cost of organisational and business process restructuring (BPR)
- Cost for change management (e.g. employee motivation)
- Cost of disruption (productivity losses)

Human costs

- Cost of management and staff dealing with procurement
- Cost of management and staff required to start-up activities
- Cost of administration and operation activities
- Cost of in-house application development
- Cost for user training
- Cost for staff turnover
- Changes in salaries

Direct costs

Initial costs

- Hardware cost
- Software cost
- Cost of software and data modifications
- Cost of installation and configuration Consulting cost
- Infrastructure cost (storage, workplace design, connectivity)

Ongoing costs

- Training cost
- Maintenance cost
- Support cost (system support) Standard development cost Upgrade cost
- Rental cost (licenses, broadband connectivity, etc.)

5. Concept Network II: Benefits

Because technology benefits are context-specific, the benefits suggested here are not fully in line with the model of Oesterreich and Teuteberg.

- Value/cost of captured design errors and the role of this in reducing re-work (during construction).
- Design optimization and value added to owner and contractors (through multidisciplinary analysis, formality of review).

  - Enhancing design quality: better (embedding and implementing best practices and knowledge), making the design more economical (removing waste and redundancies) and more constructible.
  - Enhancing design accuracy and consistency (between BIM and specifications): reducing the chances for conflicts, RFI, claims/change orders.
- Advancing BIM to the next level and realizing additional values of fuller BIM implementations.
- Efficiency of the design process (value added to the design firm itself, beyond capturing errors):
  - Reducing the review time and effort—mainly for code compliance, but possibly for checking compliance with internal organization needs.
  - Easier and fuller consideration for new features: new material, design approaches, etc. (making the assessment safer and more reliable).
  - Enhancing the training and the learning curves for new staff or for adoption of new technologies (making the assessment of new features faster).
- Professional liability and insurance (for design firms).
- Realizing the benefits of intelligent (not just smart) buildings (beyond the value of accelerating this feature—considered above).
  - The net gains in operations (mainly in real-time energy analysis).
  - The added market value of an intelligent building (customers willing to pay more for an AI-enabled facility due to the image and comfort/appeal).
- Organizational efficiency, resilience and competitiveness: the value of ARC as linchpin for AI (irrespective of BIM).
  - Contribution to the overall benefits and advancement of process automation.
  - Advancing innovation capacity, organizational abilities for change management: AEC is up for significant change, where innovation will define competitiveness. The introduction of ARC is a testbed for examining organizational abilities in change management and promoting newer horizons of work. In other words, by embarking on ARC the organization can assess and increase its innovative and resilience—this in itself is valuable. Capturing, formalizing and using the rules is one of the key means to make explicit the tacit knowledge of an organization. The knowledge gained from implementing ARC will expose new knowledge that was “unknown”. It will also make it easier to experiment with new ideas.

6. Concept Network III: Methodology

For long, we have been locked into the mode of dollar-crunching for savings during the design (sometimes, construction) phase. Love et al. (2014) presented a wider scope of benefit realization and means to evaluate value. This fresh look at the methods and perspective of defining and measuring benefits can be very helpful. In the same vein, the work by Zheng et al. (2019) on SVN (Stakeholder value networks); the work on Social network analysis (for stakeholders) by Hattab and Hamzeh (2015); and the economistic methods by Lee et al. (2015) represent benchmarks for diversifying our methods. Figure 2 below is extracted from Zheng et al. (2019) and showcases the advantage of using a value network in the analysis. It allows for listing stakeholders as well as who provides which value to who. Such value flows can change based on the boundary conditions of the case; and the valuation of such value streams can be conducted in different ways.

Developers of new business cases in ARC should try to discuss the main features of their methodology along the following themes.

- Analysis approach
- Data: size, nature (objective, subjective, measured, assessed) and quality
- Methodological assumptions
- Redundancy in model costs
- Redundancy in model benefits
- Overall redundancies with other costs and benefits (of other processes in the organization)
- Accuracy and range of values
- Repeatability

7. Concept Network IV: Boundary Conditions

Every business case will have limitations and specific context. The developers of these business cases must discuss the following elements when submitting a business case.

- Extent of BIM use in the project
- nature of the projects studied: domain, size
- PDS
- Role/domain of ARC: design errors,
- Type of ARC: rule-based, MVD, semantic (ontology, NLP).
- time and geographical spans
- Boundary condition assumptions

8. Concept Network V: Stakeholders

The nature and the role of stakeholders should also be discussed. Developing the value proposition, costs and benefits relative to each stakeholder should be encouraged.

- Role in project: owner, developer, designer/consultant, contractor, subcontractor
- Level of engagement
- Level of BIM maturity

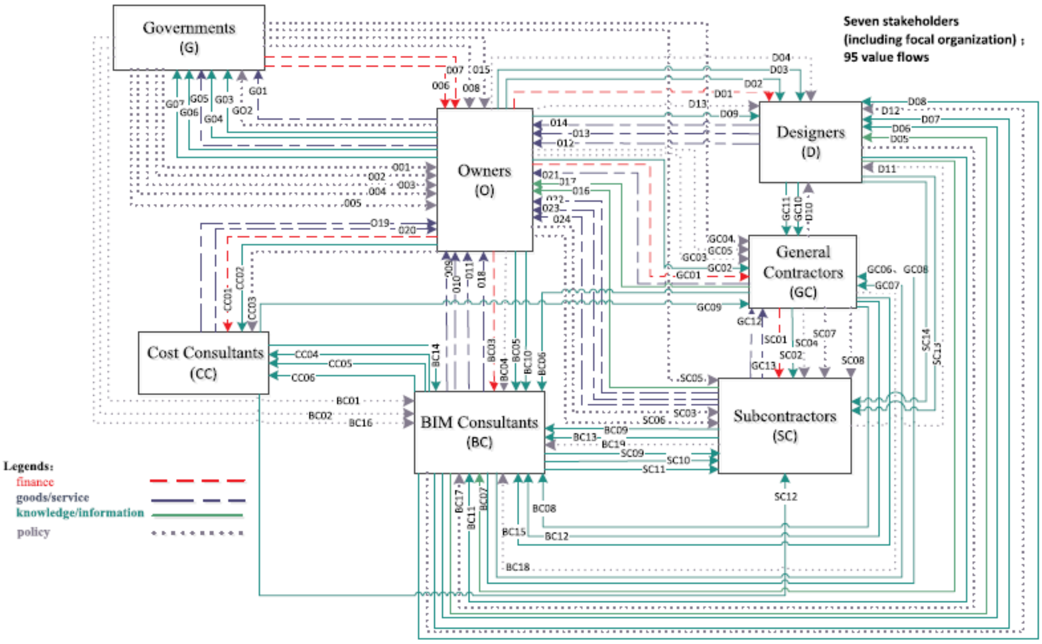

Figure 2: Sample Value Network for BIM usage (extracted from Zheng et al. 2019)

Appendix A: Applications of Automated Rule Checking

Research into automating code checking goes back to the 1960's. Fenves (1966) was one of the first to introduce the idea. He and others developed means for interpreting rules (Fenves et al., 1969 & 1995); identified requirements to digitize codes and for structuring and managing rules (Garrett and Fenves 1987); suggesting approaches for processing non-measurable rules (Balachandran et al. 1991); encoding regulations into knowledge-based system (Delis and Delis 1995); and testing the development/ application of rule-based systems.

Initially, the main approach for representing rules was through decision tables. The table includes a set of conditions that should be tested in certain situations, along with appropriate actions to be taken based on the values of the conditions (Fenves et al. 1969). This approach was used to formalize some specifications—for example, those of the American Institute of Steel Construction (AISC), including representing individual rules and relationships between rules (İlal & Günaydın 2017). However, follow-up systems have used, almost unanimously, IF-Then approaches instead of decision tables (Rosenman & Gero 1985; Dym et al. 1988). This was later extended into a more sophisticated use of predicate logic (Rasdorf & Lakmazaheri 1990).

The IF-Then approach was implemented in a variety of commercial expert systems, for example: BCAider (Sharpe 1991) by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. Garrett and Hakim (1992) and Waard (1992) developed an object-oriented model of building codes, where building elements are to be linked to the rules applicable to them. Yabuki and Law 1993 combined predicate logic and object-oriented modelling approaches to represent and process building codes. Kiliccote and Garrett (1998) introduced elements of context-sensitivity to the analysis through re-organizing the codes through a set of rules that reflect certain elements of the design. A software (called REGNET) was developed by Kerrigan and Law (2003) to determine the applicability of various codes under given building conditions, based on a question-and-answer user interface.

It was the advancement of IFC in the late 1990s that moved ARC to a different level (Yang and Xu, 2004). Since then, the process of rule checking has typically used four major stages (Dimyadi et al. 2015):

1. Rule interpretation: translating the natural language of the code into formal computer-processable form (a list or a table consisting of parameterized rules). This has been typically done through a logic-based mapping by humans from natural language to machine-readable format. The rules, built in IF-Then format, can define the condition or context under which they will apply, and the properties that will be used in the assessment.
2. Model preparation: using one or more model view definitions (MVD) to specify and assure the existence of needed parameters in the BIM model. This is because a generic parametric model is not enough to conduct rule checking. The data needs for a rule checker are more extensive than the needs of typical BIM tasks. Each object must include the minimum set of properties included in the rules.

3. Rule execution: pre- processing and post-processing of rules and conducting the actual checking. The building components are to be mapped to the applicable rule sets by name, type, or other attribute(s). Next, the satisfaction of the IF-Then rule is checked. Complex algorithms may be required to resolve conflicts.
4. Reporting: graphical or text results with a reference back to codified source rules.

A.1. Regulation compliance

The first and most notable area of implementation of IFC-based ARC is in regulatory compliance. Today, several national systems exist for automated review of regulations. Many of these systems were based on earlier research work. For example, in the area of occupant management, some of the early work (see for example, Han et al. 2002) presented methods to facilitate conformance and applicability analysis for accessibility. This continued to higher levels of sophistication. For example, Lee et al. (2010) developed a new approach for checking occupant circulation rules automatically in the US Courts Design Guide. This was based on computational approach called the Universal Circulation Network (UCN), where distances between buildings are modelled as length-weighted graph. They implemented the approach as a plug-in on top of the Solibri Model Checker (SMC).

One of the earliest and the most successful use of ARC in regulation compliance is FORNAX (Liebich et al 2004). It is a BIM-based system within the construction administration system, CORENET (COnstruction and Real Estate NETwork), which started in 1995 by the Singapore Ministry of National Development. It consists of three platforms (Khemlani 2006): e-Submission, for project submission and document approval; e-PlanCheck, for automated code-checking; e-Info, a central repository of building and construction-related information in Singapore. e-PlanCheck is implemented on top of FORNAX, a platform developed by novaCITYNETS that adds higher-level semantics to IFC. Each FORNAX object includes additional attributes needed for code-checking (Lee et al. 2012). The rule checking focused mostly on spatial and accessibility requirements, and building services (Tan et al. 2010). The initial target areas were access and exit requirements, fire safety regulations, environmental health requirements, vehicle parking, waste and drainage provisions, and Gas services in buildings.

Statsbygg is the Norwegian agency managing government properties and is its advisor on construction and property affairs. It initiated the ByggSøk Project, which includes three components: e-Information System, for publishing information required to prepare a plan or an application; e-System for zoning proposals to streamline communication between developers and government; e-Building Plan Application, which is an online submission system (Eberg et al. 2006). The HITOS project implements several aspects of ARC. The building model data is stored and accessed through the EDM (EXPRESS Data Manager). The rules are mapped to IFC products and executed through SMC.

It also uses some CORENET features, which allows adding additional code-related parameters (Martins & Monteiro 2013).

In Australia, the BCAider is an early, non-BIM system developed by CSIRO in the late nineties. It supported compliance of designs against the Building Code of Australia (BCA) (Drogemuller et al. 2010). DesignCheck, also by CSIRO and the University of Sydney, is the current BIM-based system. It utilizes EDM for encoding and checking on barrier-free accessibility rules (Martins & Abrantes 2010). Instead of SMC, EDM allows direct coding into EXPRESS, as the central platform, performing model management features, rule encoding, and rule execution.

In the United States, the General Services Administration (GSA) issued several BIM guidelines and funded a code-checking system for spatial validation in US courthouses based on SMC (Eastman et al. 2009). The SMARTcodes project in the USA introduced semantic representation as part of its work on codifying the International Code Council (ICC) code. Using an ontology and web-based interface, users select written rules and the SMARTcodes builder identifies key phrases and their logical role. It, then, formalizes the phrase using terms from a dictionary of properties. The SMARTcodes are modeled based an approach called RASE (Requirement, Applicability, Selection, Exception). A building code rules is composed of: Requirement (the conditions that must be satisfied by one or more features in the building); Applicability (which aspect of the building the requirements apply to); Selection (instantiation of the rule to a specified cases among applicable elements); Exception (where the check is not required/applicable). SMARTcodes only deals with IFC-compliant designs and uses SMC and ABC’s XABIO (Hjelseth & Nisbet 2011). The main target of the platform is energy conservation rules, with focus on window and door assemblies, sealing of building envelop and insulation criteria. GSA supported additional work on rule checking for circulation and security validation in Courthouses. Also in the USA, Fiatech’s AutoCodes was the regulatory streamlining initiative in their extensive architecture for smart/intelligent construction.

In Korea, SEUMTER (Lee 2011) is a base architecture/platform that was developed to support automation of all the processes and documents related to housing administration! It includes several implementations of ARC. The main areas of applications are: fire protection, fireproof, regulations related to site, building scale, usage and building structure. Recently, Kim (2012) developed a rule-set for regulation check for emergency elevator and fire safety zone based on SMC with additional applications to rule-based checking modules for the evacuation of super-tall buildings.

The long history and rich research in regulation checking is a testament for the need for ARC. However, ultimately, the best indicator for the value (and business case) of ARC is the sustained existence and increased use of commercial software systems—for example, Tekla Structures and Solibri Model Checker. SMC, while focused on special attributes can be used to develop additional rule-sets in the Java API environment. It makes it easy to develop a prototype system for early application. However, there are disadvantage involving the limitations of API modules and the dependence on SMC.

Issues and trends in regulatory compliance

The long history of ARC in regulation checking provides some of the best opportunities to understand the challenges and the determinants of the business case. Some of the key challenges include the following:

The extraction of relevant data from building objects is the key step in ARC. The data can be made available by the designer (manually inputting the data); the computer can extract data from related sources (such as other models and/or databases); or using an iterative analysis model that generates complex information from basic data available in the model (Martins and Monteiro 2013). Consequently, the level of design details and the availability of the required information have significant impact on the success of ARC. On the one hand, the fast-paced increase in experience with using BIM, especially in design/consulting firms, will reduce the impacts of data in-completeness and quality. On the other hand, the challenges of limited pre-project planning time/work and the increased complexity of designs themselves continues to make data completeness an issue for any ARC.

At a more fundamental level, ARC systems are dominated by hard-coding approaches, which requires a high-level of expertise in computer programming, limiting the abilities of users to contribute to adding/updating rules. This makes most ARC inflexible and hard to maintain. To overcome some of the deficiencies of hard-coded approaches, The SMARTcodes project introduced a semantic protocol (SMARTcodes Builder) for creating smart versions (tagged representations) from actual building code texts. The platform provides methods for translating natural language rules into computer code. Recent research work has proposed using an ontology for the formalization and semantic representation of building codes (see for example, Yurchyshyna & Zarli 2009). The introduction of IfcOWL is a major step towards advancing the semantic interpretation of building code/information. Natural Language Processing (NLP) techniques are offering a major contribution in the formalization of specifications into rules (Salama & El-Gohary 2013). Work on advanced use of ifcOWL, linked data systems and semantic web technology is a key step to addressing the limitations of IFC structure or depth; and the traditional lack of data or its quality (Pauwels et al. 2010). Finally, the development and use of higher level query languages (see for example, Dimyadi et al. 2015; Beach et al. 2015) is another major step towards promoting modularity, re-use as well as efficiency and adaptability. However, a certain level of human input and translations/interpretation will always be needed.

In the majority of the systems above, rules are defined top-down. An expert or a user codes the rules. Advances in NLP are promising to provide a chance for bottom-up detection of rules. Such approach opens the door for a form of machine learning system for extracting and resolving conflicts between rules. For example, Deshpande et al. (2014) proposed a new bottom-up method to capture, extract, and store information and knowledge from BIMs.

At the most fundamental level, the challenge to ARC is that it cannot be comprehensive enough given the increasing number and complexity of applicable regulations (comprehensiveness). Furthermore, any change in the building code necessitates changing the ARC system, some of which could require fundamental re-design of the system (maintainability). Further limitations of ARC are related to the lack of clear mapping between the building code documents, and between documents and code models. Finally, most ARCs can assure effective check at the individual rule level. There is limited work on preventing contradictions or assuring compliance with groups of rules. The most effective way to address these challenges could be through regulatory agencies coding their code. Regulators should start working on issuing new regulations in the form of algorithms—with proper checks/specifications on applicability and conflicts--see Wilson and Cali 2016 for interesting analysis for the role of algorithmic regulations in managing the smart city (from a legal point of view).

A.2 Best practices and knowledge encapsulation

One of the main areas of application of ARC is in embedding various best practices in BIM-based systems. IFC is a common data standard that was meant to achieve interoperability in the AEC industry. This allowed BIM systems to be a conduit for collaboration and data exchange. Several researchers have attempted to add rules on top of this data-rich environment—making BIM a platform to embed and to check on rules that reflect industry knowledge, or promote efficiency. For example, Motamedi et al. (2014) integrated the use of knowledge management (KM) and BIM to investigate an approach for detecting failure root-cause, which could help facility management (FM) and technicians identify and solve problems. Another knowledge-based system was presented by Motawa and Almarshad (2013) to capture and store various types of information and knowledge created by different participants in construction projects in order to support decision making for building maintenance. Additional research work was conducted in several technical areas. For example, supporting design and constructability of deep foundations (Luo and Gong 2015), structural analysis (Patlakasa et al. 2018) and water systems (Martins and Monteiro 2013).

The following sections discuss the application of ARC in various sub-domains. Only a very limited studies are reviewed here, as the objective is to showcase the use of ARC, not to synthesize progress done in each subdomain.

Safety analysis

One of the earliest areas for this line of research work was in regards to the evaluation of safety. The design stage is the best opportunity to study, identify and mitigate most safety risks. Potential hazards could be identified and corresponding measures could be chosen. Sulankivi et al. (2013) developed a BIM-based system to simulate construction sequences and then used a rule-based system to identify compliance with safety best practices. Zhang et al. (2015) transferred the regulations of Occupational Safety and Health Administration (OSHA) and some best practices into table-based safety rules. They implemented these into a system to plan and simulate safety issues at the design stage. Similarly, an open BIM-based evacuation regulation checking system for high-rise and complex buildings was developed by Choi et al. (2014).

The system, also, generates several scenarios and matches them with a set of applicable rules to help study building evacuations.

Semantic solutions were introduced by many researchers to help address some of the challenges of rule subjectivity. Qi et al. (2011) developed a dictionary of rules and best practices suggested by construction workers, which were encapsulated into a risk identification module. A rule-based system implemented these rules into BIM.

Energy analysis

BIM has been used to help coordinate energy analysis in buildings. Lately, many research projects attempted to introduce ARC into the domain (see Eleftheriadis et al. 2017), with varying levels of success (see Bueno and Fabricio 2018). Other studies expanded the analysis to assessment of carbon footprint (see Yang et al.), where the BIM model was used to extract data (materials, equipment, and other attributes). On site tasks as well as building operations scenarios were both simulated. Energy usage was calculated through accessing the Chinese LCA software eBalance, Ecoinvent database and European Life Cycle Database.

Design coordination and project management

The role of BIM as a platform for coordination and the exchange of product data has been complemented by ARC to help increase the efficiency of the design and project management processes - particularly in regards to managing the flow of information. For example, Cooke et al. (2008) proposed a web-based decision support system, ToolSHeD, to integrate assessment of safety risk into design process. A set of rules were obtained from industry standards, national guidelines and codes (of Australia). They were used to support more efficient flow of information and in assessing risks in complicated situations.

A very promising domain is the integration of BIM and business process rules. Green 2.0 (El-Diraby et al. 2017) introduced a link between BIM and open source BPM (business process modelling) systems, as well as social network analysis. The aim was to capture and link BIM objects and design activities to their corresponding processing tasks. This allows managers to monitor how long do design activities (or elements) take. They can also extract patterns for further analysis.

The business side of facilities

A major shift in the use of BIM in the AEC industry is its introduction to supporting non-technical tasks - particularly business tasks. The management of supply chains is one of the key areas that has received a significant interest from researchers in this regard. First, researchers considered identification and extraction of component information across platforms (capturing and integrating information of the physical elements). Čuš-Babič et al. (2015) used simplified rules to map information between design, manufacturing, and construction schedules to facilitate a more synchronized supply chain. Second, researchers worked on optimizing the linkage between processes. For example, Bortolini et al. (2009) considered site logistics to support planning and control of engineering and ordering prefabricated systems. Such systems are promising in supporting the enhancement of material supply chains, particularly in assessing and optimizing 1) lead time, 2) schedule uncertainties, 3) unanticipated conflicts, 4) importance of diversified partners, and 5) the optimization of the manufacturing facility output. Finally, some researchers addressed the automation of the overall supply chain. This is becoming increasingly possible due to the advances in process modelling and automation rules and advanced schedule management/ generation algorithms (see Hajdu 2018).

Finally, e-procurement has always been an area of interest for researchers in ARC - particularly in the area of e-bidding. However, the limited abilities in semantic rule analysis is hindering the progress in this regard. Any significant implementation of ARC in this domain will require an effective integration of data/information between BIM and the RFQ (request for quotes) or other bidding documents. Furthermore, it is hard to convert individual building objects (from BIM) into the bid elements. BIM objects tend to be very elementary and tenders focus on aggregate levels of products and services.

Issues and trends in using ARC for best practices modelling

Much like most ARC application cases, the complexity and subjectivity of rules are a major challenge in this domain. Furthermore, context and cross-domain conflicts have significant impacts on implementation of such work. Most of these systems are limited to specific scenarios, which makes the quantification and valuation of benefits a hard task. Most of the systems in this area of ARC application are sensitive to the quality of scenarios generated. Finally, there is very limited consideration of cross-system analysis or data integration.

As rule management languages and linked data systems advance, some of these challenges could be addressed. Bottom-up rule extraction and the linkage to semantic analysis of specifications and to BPM could be also a major help in revolutionizing ARC applications in this domain. With these tools, rules can be extracted more efficiently and consistently, managed more effectively, and integrated across domains.

The possible bigger influence on advancing this theme of ARC is the increasing interest in business management and process automation in the AEC industry. As usual, after seeing the clear advantages of such systems in other industries, our industry is catching up.

A.3 Intelligent facilities and data analytics

Traditionally, BIM role in advancing smart facilities was limited to providing visualization and possibly location information: where is the sensor that is providing real-time data. However, lately, with the advent of IoT and data culture, BIM is having a more “active” role. This is mainly related to advancing the analytics of data in smart facility. The aim here is not limited to traditional application in automating parts of the building (making it smart). Rather, making the facility intelligent through using data analytics and machine learning to detect patterns and provide a more adaptive level of interaction. Some of the applications in this regard relate to enhancing occupancy-centric controls (i.e., occupancy detection and forecasting) and occupant behaviour-centric controls (i.e., occupant behaviour modelling). In both cases rule-based BIM systems are needed (see for example the review by Gunaya et al. 2019)

Even the traditional usage of BIM as a "location" service is advancing to levels that includes rules. For example, Park et al. (2017) used BIM information and information from Bluetooth Low Energy (BLE) to enhance the accuracy of occupant tracking systems. In this self-correcting system, a set of rules are needed to validate and integrate the data from both sources.

Another rule-based system is emerging in the automation of construction site tasks—especially in relation to managing prefabricated components. This is no longer just limited to tracking the location of components. In one case, Zhong et al. (2017) developed a multi-dimensional BIM platform with IoT-enabled real-time visibility and traceability for the prefabrication process. The platform captures real-time data where different end-users can monitor the project status and progress. A set of rules are used to help them study the changes/ impact on cost in real-time. Another system was developed to manage on-site assembly through collecting real-time data during on-site assembly of prefabricated components using the radio frequency identification (RFID) technology. One of the key rule-based features in this system is an error detection and alerts mechanism (see Li et al. 2018). Every precast component has a specific RFID tag, which are used with Geo-location rules to coordinate the location at which an element is installed based on the BIM model.

The domain of application in this domain covers also the use of ARC in real-time "modelling" and prediction of building operations. Furthermore, recent work is also addressing building decommissioning (see Akinade et al. 2015). The potential for integrating real-time data expands beyond sensors and RFID to include drones and, soon, robotics. Finally, new applications are also using rule-based and BIM-enabled systems can, very soon, be extended into "intelligent" material. Moreno-Navarro et al. (2019) studied the potential of coded asphalt in guiding autonomous vehicles. This project used intelligent asphalt that has been codified using magnetic particles in order facilitate the driving of autonomous vehicles (AV). The whole domain of "infrastructure for autonomous vehicles" has received very limited attention compared to the extensive research conducted on AV technology.

Issues and trends in intelligent facilities and data analytics

Massive investments by large corporations and research institutes are making strides in the domain of smart city - particularly the advancement of mobility as a service, ride sharing and automated vehicles. Such domain is an AI-native, with ARC at its core. However, the number and depth of AEC-related ARCs in the design and operations of smart city systems lag significantly. The prospect of codification and real-time automation and data collection using BIM in this sphere are a major opportunity for BIM-based ARC. Based on the location of the vehicles and the attributes of nearby street furniture and features (extracted from a BIM), real-time information and suggestions can be communicated to the vehicle. For example, whether an AV is in the wrong side of the street (such as lanes for use only by public transport), or sections with different speed limits.

Paying attention to this theme of AEC ARC will not only benefit from the significant investments being made in smart city R&D, but also the significantly sophisticated methods and tools.

A.4 Design automation

The next frontier for ARC is in reversing the rule application objective and approach: instead of checking on the design compliance to rules, research into design automation uses rules to generate the design itself. In other words, rule can be applied in a different perspective: instead of compliance checking, it can be directed at constraint solving (Martins and Monteiro 2013). In this mode, a set of rules are to be used to achieve/overcome constraints applied to the design, so that the system provides the optimal solution. An ARC in this scenario is a collection of rules and constraints that can be iteratively used by the computer to generate designs—more specifically, and for the time being, layouts (see for example Merrell et al. 2010). Some of these rules can be an input by the administrator (designer) or, possibly, through an intelligent agent.

Beyond layout generation, the integration of IFC parametric representation of product attributes (particularly, the geometric attributes) with semantic systems allows multiple analyses to be conducted, including programmatic spaces, building circulation, energy consumption, and preliminary cost analysis (Sanguinetti et al. 2012). This pre-analysis, in contrast to the traditional post-analysis, is some of the earliest applications of (truly) advanced artificial intelligence in ARC: rules that build the building instead of checking on it. Repeated use of such systems is bound to create datasets large enough that machine learning can be implemented, where through recognizing pattern, rules can be generated for us. To this end, attempts have been made at modelling rules in a consistent manner. For example, Hou and Stouffs (2018) developed a design grammar (for layout configurations) simply by organizing rules based on their sequence, selection and iteration. They used different deductive strategies and a set of constraints to develop near-optimal options. However, the test results showcased the deficiency of bottom-up approaches in predicting the effect of an action on the future design.

Of equal value to the automation of design is the work on automating schedule (see the work of Hajdu 2018 in formalizing “precedence” in construction schedules). This can help in automating and iterating the development of construction schedules. The integration of design and schedule automation is key to optimizing prefabrication, just-in-time delivery, 3D printing of facilities, and automated building construction (using robotics).

A.5 MVD

One of the key challenges in BIM usage, which is directly related to ARC, is the lack of a data and modelling quality assurance process. This is where MVD plays a major role (Eastman et al. 2009). In one view, MVD is the most basic of ARCs. It applies rules to check on the compliance and quality of BIM data. The information quality analysis can assure compliance of building objects, their attributes and interrelationships to a set of requirements or rules needed for an ARC or for meeting certain (submission) standards. The latter has received more attention from researchers and public agencies as it can make e-permitting process much faster: it automatically assures that the submitted BIM has all the needed data. Traditionally, MVD development focused on geometry data. Recent research is now dedicated to specific domains, which includes more domain-specific rule and (data/modelling) compliance-checking. For example, a proper MVD for energy analysis should contain the following data (Pinheiroa et al. 2018): HVAC objects, controls, operating schedules and simulation parameters in the data exchange.

The rules applied in data/model compliance checking can include the following (Lee et al. 2016):

- Checking for correctness of value, including checking the value of an attribute being of a defined (required/appropriate) type;
- Checking the existence of value: checking null, existence of an instant attribute as well as evaluating the upper and lower limits (cardinality);
- Check uniqueness of values: uniqueness with the file, including comparing values within a model and checking the uniqueness in aggregation (comparing an instance within a given list);
- Checking type: reviewing the correct type of entity; checking subtype entities; and
- Checking for referential entity: checking a referencing entity and checking an inverse relationship.

The latter checks are more complicated and domain-specific and will be more challenging than the earlier ones (Solihin and Eastman 2015).

Product query and databases

The simplification of the ability to find entities and their attributes and the values of these attributes is essential to making ARC more feasible. BIM data is largely locked inside the data model of its respective authoring tool. Typically, users have limited abilities to do meaningful queries. Even with the use of IFC getting the data out of BIM is still not an easy task (Solihin et al. 2017). Research on developing searchable databases of BIM data uses a variety of rules to enable users to query the models more effectively.

A.6 Semantics

The increasing complexity of interpretation of code/rules has prompted several research works on the semantics of ARC. First, this covered the development of ontologies. Some of these aimed to bridge IFC (graphical/physical data) to domain knowledge. For example, Kim et al. (2018) suggested an ontology to link IFC to facility management (FM) practices. The ontology provides a link to IFC objects and work information in order to help search historical FM work records related to a current job. In addition to the role of ontology in bridging the data representation gap, more sophisticated work on the use of ontology in AEC was done in relationship to the core value of ontology: capturing domain knowledge. For example, developing an ontology-based system for building cost estimation by Lee et al. (2014) using the concept hierarchy and axioms (embedded within the ontology), this system is able to search for the most appropriate work items (in their case study, limited to tiling). The specifications of work tasks (such as room usage, building element, finishing base type, and finishing thickness) can be extracted from IFC data. Using a set of rules, work items and expected work tasks can be inferred from the semantic inference engine, including tile size, tile thickness, tile type, tiling type, tiling material type, joint width, and joint material type.

The ontological-based inference process (a sort of ARC) reduces the need for an estimator to subjectively search for an appropriate work item. The authors point out two important issues: 1) the importance of collaborative formalization of knowledge— "if ontology is elaborately defined by the knowledge of experienced engineers, then accurate and consistent results can be obtained". And, 2) ARC is a major boost to BIM usage and effectiveness: "In addition, the proposed process will assist cost estimators to use BIM data more easily, and it will help the expansion of BIM-based construction management."

ifcOWL ontology is a major step towards enhancing the whole domain of BIM-based semantic analyses and ARC. Much more advanced than IFCXML, it is an ontology equivalent to IFC schema written in the Web Ontology Language (OWL). An option is available to present design attributes/data in RDF format (Resource Description Framework), a general information modelling method. This has allowed a significant advancement in ARC: the ability to use advanced query languages. For example, Krijnen and Beetz (2018) introduced a SPARQL (SPARQL Protocol and RDF Query Language) engine to enhance the ability to query IFC files—this task is often incomplete due to the limited semantic representation in IFC. The difficulty is further compounded by the increasing size of data sets in complex facility projects. This limits the use of clear-text encoded RDF in many cases. The SPARQL implementation is based on ISO 10303-26 and relies on an open standard for organizing large amounts of data: Hierarchical Data Format version 5 (HDF5). Due to hierarchical partitioning and fixed-length records, only small subsets of the data are read to answer queries, improving efficiency. A prototypical implementation of the query engine is provided in the Python programming language.

Natural language processing (NLP)

There is a limit to how many ontologies can be developed and co-used. This is why natural language processing will remain a needed tool in any semantic system. Uhm et al. (2015) formulated the requirements for developing computer-interpretable rules for checking the compliance of a building design in a request for proposal (RFP) in South Korea. This work showcases the advantages, limitations and complexity of NLP. Each RFP contained over 1800 sentences, with only three to 366 sentences that could be translated into a computer-interpretable sentence. Hospitals had the largest number of sentences (about 1800–1900 per RFP). However, only 10–20% of sentences could be coded. In comparison, in the case of a courthouse, 55% of its 166 sentences were coded.

However, hospitals (and office buildings) have more formalized rules (in the form of tables rather than in natural language). This study deployed context-free grammar (CFG) in natural language processing, and classified morphemes into four categories: i.e., object (noun), method (verb), strictness (modal), and others. The subcategorized morphemes included three types of objects, twenty-nine types of methods, and five levels of strictness.

Recent trends in ARC are targeting more advanced features for semantic representations (both through ontology and NLP) and rule coding languages. For example, see the work by Beach et al. (2015) and Fortineau et al. (2013) who developed a semantic platform for interoperability, logic-based modelling for automated regulatory compliance. Zayaraz (2015) used a language extraction ontology and Naïve-Bayes classifiers for concept relation detection in a generic question answering system. Nalepa and Bobek (2014) investigated context-aware reasoning methods. These approaches were used to upgrade (and add intelligence to) traditional models in ARC—for example, pathways and circulations in hospitals (Yao and Kumar 2013), evacuation and fire management in high rise buildings (Choi et al 2014).

One of the key areas where such advanced systems are being directed, with great potential for significant advancement in automation, is in developing rules for business process management. Njonko et al. (2014) developed a controlled natural language for process specifications. Pham et al. (2015) developed a rule-based language for integrating business processes and rules. Aichernig, and Schumi (2016) investigated the extraction and testing of properties from business rule models. Bernardi et al. (2016) studied the life cycle activities and their relationship to validating business rules.

A.7 Challenges to ARC adoption

For long, the main challenges for BIM were to make it usable; and to convince the industry to use it. Now, with the wide spread of BIM usage, we move to new challenges - particularly in relation to model complexity. ARC implementation is faced with the old and the new: we need to make ARC usable and get the industry to use it; and we need to conduct that with today's increasingly sophisticated BIM and work environments. This is not limited to the increasing complexity of the technical aspects of design (which makes BIM usage more challenging), but also in situating BIM and ARC within the mushrooming challenges of modern organization: process automation, artificial intelligence and data analytics (structured and unstructured). Of course, the advancement of the latter disciplines in other domains, is an opportunity (for learning and benchmarking) to AEC.

The big challenge for ARC is not the technology or coding—much progress is being made on this front. The challenge is in its governance and business management. Vass and Gustavsson (2015) identified nine business barriers to BIM implementation, which can be seen as all applicable to ARC.

1. Changing work practices
2. Providing education and learning

3. Developing a mutual BIM definition
4. Evaluating the business value of BIM
5. Demanding BIM in procurement
6. Creating incentives
7. Including maintenance department
8. Creating new roles
9. Managing interoperability

It was surprising that, contrary to common belief, this study disputed that leadership by public clients can act as change agents in the AEC industry by demanding BIM in procurement. This is especially interesting given that the research work considered the context of the Swedish construction industry (where government leadership in BIM implementation has been seen as an example)!

In fact, much like BIM, the success factors for ARC can be categorized into two broad themes (Mom et al. 2014): ‘support from top management’ and ‘functionality’ of tools. ARC will only happen with agility and good governance and business management practices, including (Krystallis et al. 2016):

- Social-organisational (Resistance to change)
    - Lack of trust in and apprehension towards new technology
    - Lack of [ARC] understanding
    - Variations in practitioners’ skills
    - Lack of [ARC] training
    - Lack of motivation
    - Clients’ awareness
    - Adoption of traditional practices and standards
    - Avoiding/hiding potential risks and liability for mistakes
- Financial ([ARC] adoption cost)
    - Personal Indemnity Insurance (PII) is not covered
    - [ARC] training cost
    - Limited budget
    - Expensive human-based services costs
- Technical (Maturity of BIM-based technologies)
    - Interoperability issues
    - Issues with existing BIM modelling and collaboration tools
    - Massive data inputs/outputs
    - Massive data and limited data storage

  - Limited accessibility and access rights
  - Lack of data sharing mechanisms
  - Lack of data tracking, checking and versioning control mechanisms
  - Difficulties coordinating large BIM models
  - Lack of notification mechanisms
- Contractual (Contractors benefit from confusion)
  - BIM contracts are not yet mature
  - Lack of BIM [and ARC]-related aspects in current contracts
  - Failure to address BIM [and ARC] legal concerns in current contracts
  - Contracts need to accommodate changes in BIM collaborative environment
- Legal (BIM models ownership: intellectual property and copyright concerns)
  - Liability for wrong or incomplete data
  - Lack of legal considerations in existing BIM contracts
  - Lack of legal framework for adopting collaborative BIM
  - PII does not cover legal aspects of collaborative work

Appendix B: the Business Side of ARC

B.1 Benchmarking studies on the ROI on BIM

Numerous studies have analysed the benefits of using BIM. As a sample, Jin et al. (2017) developed the following list, which encompasses the main categories of benefits:

- Improved multiparty communication and understanding from 3D visualization
- Positive impact on sustainability
- Improved operations, maintenance and facility management
- Improved project process outcomes, such as fewer RFIs (i.e., requests for information) and field coordination problems
- Positive impact on marketing
- Increased application of prefabrication
- More accurate shop drawings
- Lower project cost
- Shortened construction duration
- Improved productivity
- Improved jobsite safety
- Shortened duration in the project planning stage

Studies that considered values derived from BIM utilization fall into two main categories (Lee et al. 2015): 1) those that identify appropriate metrics with which to measure BIM values for individual stakeholders, and 2) those that develop an applicable framework or process to assess values and to guide BIM best practices. In both cases, some research work attempted to investigate the value gained by specific stakeholders such as owners (Love et al. 2014), designers (Son et al. 2015), and contractors (Pryke 2012). Others (see for example, Dehlin and Olofsson 2008) have focused on studying the effect on the project as a whole. In general, researchers used surveys, case studies, individual analyses, and theoretical conceptualizations. Among these, case studies are most commonly used. They typically report on the value of BIM implementations with their quantitative savings. A set of studies have considered cross-case comparisons in project performance achieved using BIM (Zheng et al. 2019).

Sadly, the whole domain of cost/benefit analysis of BIM is marred by controversial estimates. Some of the estimates for ROI on BIM usage have reported wide ranges (see Won and Lee 2016): Giel et al. 2011: 16%–1654%; Gilligan and Kunz (2007): 140%–39,900%; Yong et al. (2008): 300%–500%; Lee et al. (2012b): 22%–97%; Azhar et al. (2008): 229%–32,900%; and Sen (2012) 735%. These huge variations are mainly due to the different benefit realization mechanisms utilized, but also due to a lack of tools that are capable of quantifying intangible values. Being aware of this deficiency, Azhar et al. (2008b) used comparative case studies to examine the various tangible and intangible values achieved by all stakeholders through implementing BIM. However, although many studies have discussed the intangible values, only a few have formally analyzed them (especially as they flow among different stakeholders).

Few studies have tried to follow a more objective approach. One of these is the study by Lu et al. (2014). They considered the time-effort distribution curves of real-life AEC processes. Analysing data from two projects (one with BIM implemented and the other without), they found that BIM implementation increased the effort input at the design stage by 45.93% (which amounted to 100.9 HKD/m^2 increase in this study). But, at the building stage, this has contributed to decreasing the cost per square meter by 8.61% (which amounts to 591.76 HKD/m^2 saving in this study). Taking a holistic view of the AEC processes, BIM implementation contributed about a 6.92% cost saving (which amounts to 490.86 HKD/m^2 saving in this study) to the sample BIM project.

While these research findings can be used to justify the promotion of more widespread BIM adoption in the AEC industry, cost-benefit analysis (CBA) of BIM implementation remains hampered by a general lack of reliable data. A synthesis was conducted by Barlish and Sullivan (2012) and found that the top reasons for value in using BIM are: Schedule, Sequencing coordination, Rework, Visualization, Productivity [enhancement], and [reduced] Project cost. These were followed by the following secondary factors: Communication, [quality of] Design/engineering, detection of Physical conflicts, Labor efficiency, enhancing Safety analysis, Change orders, Maintenance applications, Prefabrication, Quality, Simulation, As-builts, and Pilot cost. Some of the reliable facts/findings they reported from four sources are as follows:

> Source 1: Cost of implementing BIM is less than 1% of the total project cost. Conversion of the 2D model approximately amounts to 75% of the total pilot cost. Identified and resolved sequencing issues that were avoided nearly saved $2 M. Physical conflicts (clash reports) saved $0.75 M. Schedule conflicts (scheduling interface) saved $1.2 M. Data conflicts (attribute management) saved $0.5 M.
>
> Source 2: Change orders as % of base contract in 2D projects: 18.42%; 3D only: 11.17%, Collaborative BIM: 2.68% (Data is based on 408 projects over past 6 years, totalling $558 M)
>
> Source 3: MEP (mechanical, electrical, plumbing) labor savings ranging from 20 to 30% for all the MEP subcontractors: "100% pre-fabrication for the plumbing contractor; One recorded injury throughout the installation of MEP systems over 250,000SF; Less than 0.2% rework for the whole project for the mechanical subcontractor; Zero conflicts in the field installation of the systems; A handful of requests for information for the coordination of the MEP systems between contractors and the designers; 6 months' savings on the schedule; About $9 M savings in cost for the overall project."
>
> Source 4: "Reduced rework: $50,000; Shortened construction durations: $10,000, Visualization (underground electrical) Sequencing: $250,000; Preassembly: $25,000; Bundling: $10,000; Shop fabrication: $25,000; Conflict checking (between trades): $4,000,000 Bulletins: $250,000; other changes — $250,000"

Recognizing the special perspective of each stakeholder can be helpful as each will be able to evaluate the benefits they specifically gain. Zheng et al. (2019) conducted a study, where they did not use the typical approach of estimating the dollar values of savings during a case study analysis. They used subjective utility analysis to help capture the value gained by each stakeholder. They observed that contractual matters establish economic relationships, while collaborative processing of design/project tasks establish social relationships. They attempted to consider both in the analysis.

They assumed that the exchange patterns in stakeholder value networks (SVN) can be divided into restricted (dyadic or bilateral) and generalized exchanges (for more background, the authors refer to Zafirovski 2005), with the former signifying a direct relationship between any two stakeholders, and the latter relationships among multiple stakeholders. Generalized exchanges are more common than restricted exchanges. They further assumed that professionals with stakeholders who adopted BIM are aware of BIM values exchanges. The research team established a network of the exchanges and conducted network analysis that could be insightful to each stakeholder (for more information, the authors refer to Feng 2013). The BIM-SVN model included 7 key stakeholders and 4 types of value flows. Using questionnaires, in one owner organization, they identified 49,775 value cycles, all of which started from and ended with the owners. The calculation of the stakeholders' BRC (benefit realization capability) and the occurrence of value flow was used to assess critical value circles, key stakeholders, and important value flows. The study found that, based on a whole network, intangible value flows represented 69% and tangible values accounted for (31%). The top ones included: “Knowledge/information” flows (38%), followed by policy flows (31%), goods/services (24%), and financial flows (7%). In this case (an owner organization), adoption of BIM was specifically beneficiary to BIM consultants, general contractors, and subcontractors. Of the nine top-ranked value cycles, six were restricted exchanges and three general exchanges. The top value flows included “More accurate bill of quantity and cost estimate” from cost consultants to general contractors; “Specialized engineering with high quality” from subcontractors to owners; and “Better design drawings conforming to requirements” from designers to general contractors.

This study makes several key contributions. First, the applicability of Social Exchange Theory (SET) and SVN in the AEC industry. It highlighted the significance of intangible flows to promote value delivery among BIM stakeholders. Second, standardized values for the individual stakeholders in the BIM-use supply chain were created, allowing them to be characterized and compared and thus potentially contributing to benchmarking value creation, exchange. The new SVN model proposed here will help stakeholders understand the value trade-offs inherent in BIM application. But, fundamentally, this study introduced a new method, focused on business side (and the use of business terminology and systems). Showcasing the use of networks to capture the value exchanges and the benefits of network analysis by this study are significant contributions towards modelling the complexity of ROI analysis issues. Similar analysis on the semantic network of benefits and costs can be equally insightful.

B.2 Evaluating the ROI of ARC

ARC ROI is hard to estimate given the limited history and span of implementation of ARC. On the other hand, the limited scope of ARC (compared to the expanded role of BIM) can make the process of the evaluation more focused. A set of related studies have quantified ARC-relevant cost and benefit items. Chief among these are the studies that quantified the impacts of incomplete design or design errors.

Incomplete design and design errors

Park et al. (2017) used an error taxonomy, where errors are divided into three categories: skill- or performance-based errors, which were associated with slips in performing accustomed routines; rule- or knowledge-based errors, which were associated with mistakes due to lack of appropriate knowledge; and intentional violations or noncompliance, which were a refusal of conducting appropriate actions. Lee et al. (2015) divided error into two levels of human cognitive performance: whether mistakes occur in a previously experienced situation or in a new one. Mistakes reflect inadequate management/practices and are harder to detect compared to skill-based slips (or lapses). Further, the causes of errors can be seen under two main categories: miscommunications between parties in a project and cognitive limitation. The intensity and chances for both increase when too much information is exchanged simultaneously.

In general, case studies have been used to evaluate the negative consequences of lower quality designs. The result is a wide range of estimates. For example, Love et al. (2017) noted that the cost of quality failures reported in the literature varied from less than 1 to over 20% of a project's contract value. The authors listed the following examples: Abdul-Rahman 1993; Willis and Willis 1996; Josephson and Hammarlund 1999; Love and Li 2000a&b; Barber et al. 2000; Josephson et al. 2002. For this topic, Prof. Love developed a wealth of studies that addressed several aspects of design quality, design errors, and re-work. In one study (Love et al. 2017), they considered non-conformances (NCRs) costs based on analysing 218 projects delivered between 2006 and 2015 in Australia. A total of 7,082 NCRs were categorized and quantified in accordance to their cost, and the differences among project type, procurement, and contract size. The analysis revealed that (1) mean NCR costs were 0.18% of original contract value; (2) structural steel and concrete works had the highest levels of NCRs; and (3) differences were found based on procurement methods and contract sizes. The cost associated with rectifying an NCR includes (1) materials, plant and equipment, labor, and supplier/subcontractor; (2) administration; (3) redesign; (4) procurement of rectification works; (5) demolition, waste disposal, and transport; (6) time delays; and (7) supervision, inspection and retesting. The burden was assigned mainly to contractors (50%) and subcontractor (43%).

Within this study, large NCRs comprised 0.67% of the total number, but accounted for 34% of the total costs incurred. The mean NCR cost was 0.18% of total project cost. NCR costs were found to be higher in projects procured using public–private partnerships and greater in those with a contract value in excess of AU$100 million.

Based on the above case, Love et al. (2017) suggested that it is possible that large project size meant larger quantities of steel and concrete, where the subcontract trades are susceptible to NCRs. Yet according to Forcada et al. 2014, other research found no significant impact of the procurement methods on the cost growth and schedule overruns experienced in building and civil infrastructure projects (Walker 1994; Love 2002; Love and Edwards 2004). In another twist, Jaafari et al. (1994) found that larger projects incur lower quality failure costs. However, Hwang et al. (2009) suggested that rework contributed most to projects with a cost range between $50-100 million. Yet, it is possible that time is the deciding factor--short projects can be seen as more “complex” or challenging due to the speed of work (Naoum and Mustaphs 1994a). In all cases, the one thing all studies agree on is that implementation of best practices, might reduce complexity and thus positively affect the reduction of rework (Hwang et al. 2009).

Costs of rework

The issue of rework has been investigated by many researchers. However, data on quantifying rework costs is difficult to obtain - particularly, again according to Forcada et al. 2014, due to the varying definitions of rework (Love and Smith 2003). Josephson et al. (2002) reported a value of 4.4%. Josephson and Hammarlund (1999) found rework cost on residential, industrial, and commercial building projects to be between 2 to 6%, while Fayek et al. (2003) found them to be from 2 to 12%. Love and Li (2000) reported 3.15% in residential projects and 2.4% in industrial buildings in one study. However, Bresnen et al. (1988) noted that facility type was an attribute rather than a causal factor (no effect on project performance). In another study, Love (2002 a) reported that direct and indirect rework costs are in the range of 6.4 and 5.6%, respectively. Oyewobi et al. (2011) found that rework is valued at 5.06% of new buildings and 3.23% for refurbished ones. Similar estimates were calculated by Mills et al. (2009). The level of value and variation was higher in civil infrastructure projects: 10.29% (Love et al. 2010); 16.5% (Forcada et al. 2014b). Love (2002b) found that mean schedule overruns were 20.7%; and that they are significantly correlated with direct rework costs.

Several features of the project contribute to rework chances and costs where ARC can help, including construction costs, project duration, gross floor area, number of stories, building type, and procurement method (Love and Edwards 2004). Controversially, Love (2002a) found that gross floor area and the number of stores in building construction projects were not significantly related to rework costs.

Alternative analysis approaches

In contrast to the typical approach of crunching dollar values associated with errors in project case, Lee et al. (2015) used a Pareto analysis of errors. They investigated warnings in BIM-based project designs. They noted that slips are more noticeable. Architectural design mistakes are hardly detected before they are implemented. Based on the error taxonomy, design errors were classified into three levels: personal, organizational, and project levels. Further, the causes were categorized into five categories (the authors cite Busby 2001 for more information): participants, designs, tools, organization, and environment. They analysed 75 cases of error. Participants turned out to be the largest source of error, which caused 27 cases (36%), followed by design (25%) and organization (25%), tools (7%), and environment (7%).

They applied Pareto analysis (the 20-80 rule) to BIM warnings. They divided warnings into three levels:

- "High priority: Warnings that have a significant impact on the quality of models and documentation and hence must be resolved immediately.
- Medium priority: Warnings that do not have an immediate impact and hence can be resolved later.
- Low priority: Warnings that have little to no impact and hence do not need to be resolved unless requested otherwise."

One of their major assumptions is that "designers would want to focus on correcting high and medium priority warnings while they may elect to ignore low priority warnings, which have little to no impact to the quality of models". With that, and based on the priority levels, time estimation was developed for warning corrections of each case project. They found that the average time of correcting annotation, information, and geometry warnings were 1, 0.5, and 5 min per warning, respectively. Post analysis interviews added the following input/assumptions: one action can solve a number of warnings simultaneously; the total time can be reduced by working on the same type of warnings in succession. Learning curve theory was then applied. The results are that the total time exponentially decreases as the learning rate increases. This finding signifies the importance of training and the effectiveness of the design review process.

Won and Lee (2016) provided an interesting study that may help in addressing a dilemma: are the realized savings due to a (partial) ARC or just because of the very use of BIM. They used a goal-driven approach to compare two cases for the role of BIM in error management. The first related to the avoidance costs of reworks due to design errors. The second was focused on the avoidance cost and reduced time by BIM-based quantity take-off. Since some errors could be found without BIM use, the avoidance cost was calculated by multiplying the likelihood of not being able to identify design errors without the BIM and the indirect rate of the project. Sensitivity analyses of the BIM ROI of the two projects were conducted. They used the following attributes in their cost calculations: software and hardware costs; costs of BIM consultant; additional labour costs for training and lower productivity (at the initial stages of using BIM). For the benefits, they used the likelihood of errors, the cost of rectifying an error and the ratio of direct and indirect costs! They also considered the reduced time delays in managing errors and in conducting quantity take off.

Finally, some research was conducted on understanding the link between an ARC system and reducing the potential of change orders. Owner changes (along with design error/omission) are considered to be a root causes of rework (Hwang et al. 2009; Love and Edwards 2013). Design inconsistencies is considered another major factor of rework (Love et al. 2009). The key solution has been to implement a quality management scheme for designs: assuring the completeness and consistency of design and specifications (Kakitahi et al. 2013). In addition, better governance and communication of the design process can have significant impact on the quality of designs, and consequently, the chances of change orders (Love et al. 1999). Khanzadi et al. (2017) investigated the causes of change orders and modelled that the root causes for the typical types of change order (note: this is one of many models). Most of the causes of design quality problems and the overall causes for change orders can be partially addressed by an effective implementation of an ARC.

- Change in schedule: Inadequate investigation of site conditions before the design phase;
- Change in design: Consultant's lack of judgment and experience;
- Change in plans or scope: Impediment in prompt decision-making process;
- Replacement of materials or procedures: Inadequate project objectives; and
- Change in specifications: Mistakes and discrepancies in contract documents.

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