Development of BIM-based model checking solutions – ongoing research and practitioners' demand.

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Abstract
Model checking is often highlighted as a major benefit of BIM-based solutions. Research in BIM-based model checking (BMC) is increasing. However, the implementation of practical solutions beyond clash detection is hard to observe. This paper explores contributing factors where research can boost the level of BMC implementation. Integrated Design and Delivery Solutions (IDDS) has been used as a theoretical framework for the analysis of the gap between research focus and practitioners' demands for practical solutions. The direction of ongoing research is provided by a literature review of recent papers presented at the CIB W78 2015 IT for Construction conference. Knowledge about practitioners' demands is gleaned from semi-structured interviews of four Norwegian expert-users in BMC. The ongoing research is technology-oriented and focuses on the development of advanced methods for auditing building models against regulatory knowledge. However, practitioners require practical solutions that are based on industry's best practices, which can readily support design processes. This gap would explain the limited implementation of BMC solutions to date. Applied research should focus more on the development of the practical solutions to accommodate practitioners' needs, which may not necessarily be the most advanced solutions.

Keywords: BMC, BIM-based model checking, IDDS

1 Introduction

The intention with this study is to explore factors where research can contribute to increased implementation of BIM-based model checking (BMC) solutions. Model checking is often highlighted as a major benefit of BIM-based solutions (McGrawHill, 2012, 2014). However, progress - or lack thereof - can be discussed. So far, the number of commercial software solutions for BIM-based model checking is limited, likewise is the situation for public services for digital processing of building permit applications (Refvik, 2013). To have a wider and more inclusive approach, this paper focuses more on integrated systems than just software technology.

Applicable solutions for checking building codes and standards have interested many researchers and practitioners since the mid-sixties. A study by Dimyadi and Amor (2013) has identified more than 300 relevant research studies traversing 40 years. The increase in research can be illustrated by the last CIB W78 IT for Construction having had 9 papers in 3 sessions, and one workshop dedicated to compliance checking. However, the research focus in the Architecture, Engineering, Construction, Operator and Owner (AECOO) industry is very low compared to other industries. Statistics Norway reports that while the AECOO spends € 1 000 per employee in research activities, the amount spent in the IT industry is € 300 000 per employee (Zachariassen, 2014).

The status reports from McGraw-Hill Construction (2012, 2014) highlight model checking as the most important current BIM requirement to effectively advance the industry, followed by improved

interoperability. Increased model quality of designed solutions is a great motivation for using BMC. Another rationale for model checking is to provide models free of issues so that data can be trusted in other software and processes.

There are no joint terms for identification or classification of BMC solutions. A study by Hjelseth (2016) has developed a classification system where BMC solutions are grouped into two main objectives; a) Compliance checking, which can be classified into validation checking and content checking, b) Design solution checking, which can be classified into smart object checking and design option checking. This paper focuses on compliance checking, which includes model validation, clash detection, content checking and similar comparative checking where designed solutions in the BIM are compared with constraints in the rule.

The research question posted at the outset of this study is: *How can research and development in BMC be better organized to increase the applicable use of BMC in projects?*

To answer the research question, this paper starts with a description of the research method. This is a broad question, and several methods and frameworks can be used. This section starts with a short presentation of the theoretical framework chosen. The Integrated Design and Delivery Solutions (IDDS) framework has been selected for structuring and analysing results in this concept study. Next comes a description of a literature review of the latest BMC related papers in the CIB W78 conference, and of interviews conducted with advanced users of BMC. The results section has two parts: the literature review and interviews, summarized according to the following three perspectives: 1) Integrated Processes, 2) Collaborative People, and 3) Interoperable Technology; according to the IDDS approach. The discussion section takes the results further and try to bring in other perspectives that were not answered directly by the results. The results must therefore be interpreted as a contribution to further discussion and not as the proposal for further research and development. The conclusion section is a short summary of impact of this study and a proposal for the direction of further studies.

2 Methods and materials

2.1 Focus in research

This study is based on a combination of literature review and semi-structured interviews with a limited number of highly qualified and experienced users of BMC. There is a general tendency in technology related research to focus on optimization of defined solutions, and how to improve this by further development of technology related functions. This study is not about BMC technology itself, and how further development of software and interoperability can solve the problems. Technology is acting in a context. In this respect, IDDS is selected as a theoretical framework for structuring of the findings.

2.2 Integrated design and delivery solutions (IDDS) as theoretical framework

This study uses Integrated Design and Delivery Solutions (IDDS) from CIB as the theoretical framework for exploring the focus in current research in relation to the demand among the practitioners. IDDS focuses on the integration of collaboration between people, integrated processes and interoperable technology (Owen et al., 2013), as illustrated in figure 1.

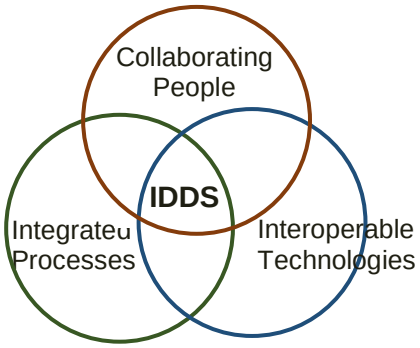

Figure 1 The three perspectives of IDDS (Owen et al.2013);
figure simplified by the authors

IDDS was developed in 2009 as a special theme by the International Council for Research and Innovation in Building and Construction (CIB-IDDS, 2015). IDDS can also be regarded as a simplification of the sociotechnical theory (Bostrom & Heinen, 1977) adapted to the AECOO industry.

BMC can be regarded as integrated deliverables. The aspects of IDDS can be embedded into BIM aspects in the following ways:

1. Integrated Processes relates to the use of standards, procedures, frameworks or methods structuring information and rules. In this study is this referred to as "Applicable processes".
2. Collaborative People relates to people using BMC in either development of digital rules or using BMC in projects. In this study is this referred to as "User involvement and design practice".
3. Interoperable Technology relates to use of digital sources and tools (IFC, XML, RDF) These three aspects are used to structure the findings in this study. In this study is this referred to as "Methods and technology".

2.3 Literature survey of CIB W78 IT for Construction papers

The purpose of a literature survey is to identify a profile of the current research. The literature survey was limited to newly published papers within code checking, and papers from the CIB W78 IT for Construction conference in Eindhoven 2015 (Amor & Beetz, 2015) was chosen, see table 1.

Table 1 Papers included in the literature survey (Amor & Beetz, 2015).

Title of paper	*Author(s)*
A Hybrid Model for Building Code Representation Based on Four-Level and Semantic Modeling Approaches	*Sibel Macit, M. Emre İlal, Georg Suter & H. Murat Gunaydın*
A Knowledge Representation Approach to Capturing BIM Based Rule Checking Requirements Using Conceptual Graph	*Wawan Solihin & Charles Eastman*
Capturing and Integrating the Design Brief in Building Information Models	*David Marchant*
Model Checking on Semantic Web: IFC Validation Using Modularized and Distributed Constraints	*Chi Zhang & Jakob Beetz*
Practical Approaches for Computable Building Codes	*Nawari O. Nawari & Adel Alsaffar*
Querying a Regulatory Model for Compliant Building Design Audit	*Johannes Dimyadi, Pieter Pauwels, Michael Spearpoint, Charles Clifton & Robert Amor*
Semantic Rule-checking for Regulation Compliance Checking: An Overview of Strategies and Approaches	*Pieter Pauwels & Sijie Zhang*
The Validation Logic and Structures of a Building Information Model Pertaining to the Model View Definition	*Yong-Cheol Lee & Charles M. Eastman*
Validation of IFC model based on high level interface: Specifications for rule checking error reporting	*Donghoon Yang & Charles M. Eastman*

2.4 Semi structured interviews

The interviews part is based on semi-structured interviews with four active and highly skilled users of BMC software, see Table 2. The interviewees all had more than 5 years of experience in the use of BMC for coordination and quality assurance of BIM in large construction projects in Norway. By selecting highly skilled users of BMC, this study could focus more on expectations about future use and development of processes and rules to increase impact of BMC. This study chooses not to focus on software issues or challenges related to lack of competency and knowledge about BMC. A study by Hjelseth (2015a) identified that there was a limited number of users of BMC software, often only one or two BIM-coordinators. This was also the situation in very large projects. These findings illustrate that use of BMC is highly related to how BIM-based projects, or how building projects in general, are organized.

Table 2 Overview of conducted interviews

Ref. ID)	Affiliation	Company size	Role	Interview duration	Interview technique
"*AA*"	Architect company	30	Architect	75 min	Face-to-face
"*AM*"	Architect company	180	Manager	60 min	Face-to-face
"*AO*"	Architects' association	*)	Academic Director	45 min	Face-to-face
"*CE*"	Consulting Engineering	1400	Engineer	50 min	Face-to-face

*) Member organisation representing 580 architectural firms with 4300 employees

3 Results

3.1 Literature survey of CIB W78 IT for Construction papers

Due to principles of anonymity, and to stress the focus on trends, the reporting of results is aggregated into general findings of each characteristic, and supplemented with comments. The survey included 9 papers on rule and code compliance checking, see table 3.

Table 3 Summary of literature survey of CIB W78 IT for Construction papers

Number listed in findings is based on 9 papers in total

Characteristic:	Numbers of authors?
Findings:	Average was 2.5, with variation from 1 to 5, with 2 as median value
Comments	No large research programs, research on low budget, see next characteristic
Characteristic:	Papers by Ph.D. students
Findings:	6 of the papers were nominated for Chuck Eastman's Ph.D. award
Comments	Relatively high number of Ph.D. students. This can influence the research in several ways; highly specialized focus, use of advanced methodology, high focus on development new solutions (compared to experiences /development of with existing), limited practical/industrial experience, small/limited projects.
Characteristic:	Papers focusing on design phases
Findings:	4 Approval phase, 1 Brief phase, 4 Not defined
Comments	The high focus on the approval phase indicate that the checking is done at a very information intensive and detailed level. Indicate also focus on advanced solutions. The problem is well defined.
Characteristic:	Papers focusing on interpretation of real codes into rules?
Findings:	2 papers included interpretation of real codes a part of compliance checking
Comments	Codes was use to illustrate applicability of developed methodology. Cases were based on prescriptive codes, not performance based codes.
Characteristic:	Paper focusing on formal representation of rules
Findings:	8 papers
Comments	The papers had in general a very high focus on demonstrating feasibility of proposed methods. This number support previous findings related to focus on approval phase and limited focus on interpretation of code.
Characteristic:	Papers based on user-defined knowledge?
Findings:	1 paper
Comments	Most paper had a fixed set of requirement or codes as foundation for demonstrated case. User- defined knowledge as related to methodology for querying, not for pre-defined checking.
Characteristic:	Study including software development
Findings:	One paper included software development as part of the study.
Comments	Software development is cost-, time- and competency intensive. This is hard to include in small projects, see the two characteristics listed first.

Table 3 Summary of literature survey of CIB W78 IT for Construction papers, continued

Characteristic:	Analysis based on theories from IS?
Findings:	0 papers
Comments	Use of IS theories was not identified, but IS related methods like ontologies, sematic web, Linked Data, recourse description framework (RDF), conceptual graphs and other *methods* or concepts was used. The lack of use of IS *theories* must be interpreted in relation to next characteristics.
Characteristic:	Study based on a Proof-of-concept (POC) approach?
Findings:	9 papers (all papers)
Comments	The research intended to have an applied focus by demonstrating applicable solutions. This is in general done by demonstrating a new method proposed by the authors. Use of IS related *methods* are often included as part of technology, but theories for implementation or processes is often missing.

Figure 2 illustrates the connection between the IDDS framework (Owen et al. 2013) and the review summary of the research focus in the CIB W78 2015 papers.

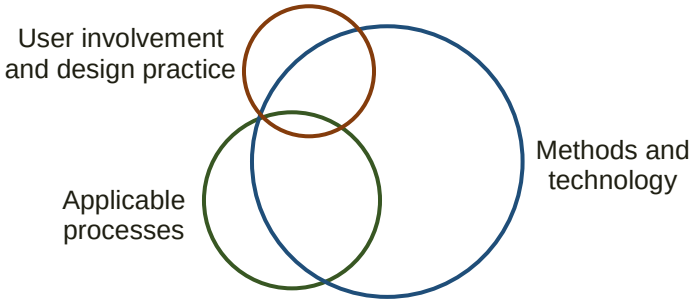

Figure 2 Summary of research focus in the CIB W78 2015 papers

Demonstrating new or improved methods was highly focused in the research papers. This was documented as proof-of-concepts and feasibility to be implemented info software (one paper included also software implementation). Technology is therefore illustrated as the dominating perspective.

The focus on integrated processes was in general related to how the methodology could be combined with other methods or be implemented into software. The integration in support of design processes was limited. This perspective is illustrated with a smaller circle with large intersection into technology.

Regarding collaboration, this was the least dominating perspective. The focus was related to exemplified by how the user could apply the methodology to develop rules or implement into software. This perspective is therefore illustrated by the smallest circle having a large intersection with technology, and limited intersection with processes.

3.2 Interviews with practitioners

This section reports selected findings from interviews with four very experienced practitioners.

High expectations to use of BMC

All interviewees expressed great enthusiasm about BMC and the development that this domain has undergone the last years. This included both BMC software, use of BIM in general, and development of processes.

All four interviewees used Solibri Model Checker (SMC), but one also used Navisworks for clash detection on infrastructure projects. They all expressed good experiences with SMC as a software tool and Solibri for being responsive to user requests.

BMC must be regarded as more than clash detection

The classic control and coordination of clash detections was used in all projects. However, BMCs have a significant potential for increased use and impact on the design process – and designed solutions.

One of the interviewees expressed this situation: "It is not hard to see the benefit of clash detection control - but there is so much more a rule checker can do" ("CE", refer Table 2).

All interviewees addressed lack of demand from clients as the most significant barrier for use of BMC in design projects. They also expressed the challenge of going from clash detection into more advanced rule checking. This can be related to BIM maturity in general and missing methods for net value of BMC in particular. Using BMC to gain benefit of BIM was mentioned as having an impact on several aspects such as changed design processes, business models, and the development of rule-sets. In this respect, the IDDS concept can be useful to distinguish between drivers for change, enablers, barriers and opportunities (Owen et al. 2013).

Increased focus on Quality Assurance (QA) and documentation

The scope of Quality Assurance (QA) has increased dramatically. There is more requirements for documentation from the client and authority. This situation can be exemplified by the following feedback from an interviewee; "QA is an expensive, but a mandatory process. Having an additional source of technical support for QA is therefore essential. In fact, this kind of support is desperately needed …" ("*AA*", refer Table 2).

BMC can certainly play a supporting role for QA, but all interviewees expressed the same opinion in that BMC is not reliable enough to be used for the formal and final approval. "It is, after all, the design team that has the responsibility" ("*AM*", refer Table 2). This implies that QA is still mainly a manual task, but BMC can support the design process. This problem has technical and legal implications. If the partners agree to use a specific digital rule-sets, then it could replace the manual checking process. However, the manual checking process is error-prone and can cause repercussions.

Trends in design processes

There is also a trend that much more is done in the briefing phase/concept phase of the project. BIM gives higher design cost, but lower project cost, which is supported by the following experience: "Our analysis shows that BIM-based engineering costs 10, 15 or 20% extra. The reason for this is that one goes further and addresses several issues. Using the Solibri Model Checker software tool improves the quality of the model so that we would then get fewer errors and problems in construction" ("*AA*"). This situation is also related to business models.

Business models

The main question here is who invests in the development during the concept phase and who harvests the benefits in the construction phase is a challenging problem to be addressed. For example, the use of lowest bid versus shared benefits. The development of computable rules is resource demanding. There seems to be a reluctance to invest in long-term development of BMC solutions.

Regarding business models, the question is about who develops the rules and who uses them. This includes clarifications on the responsibility and payment models. The implementation of best practices as applicable rules is a challenge that has to be supported with resources from the industry. The architects' association ("*AO*", refer Table 2) has started development of a BMC software solution, but chosen to await further development until a business model is clarified.

For code checking (standards and national codes), it is important that the authorities are responsible for the digital interpretation of the standards/codes for them to be considered trustworthy. So far, this is not the case.

Need for complete models for code checking

Code checking in the final phase is of course useful, but this has limited influence on the main target for the interviewees – to develop good solutions of the built environment. Codes in this respect only represent minimum requirements. Final code checking will also require a complete model with a high level of detail to match the level of detail in the regulations.

BMC to activate new user groups

BMC can also be used for enforcing collaboration and change in processes. Checking what is not being checked today and getting 2-D engineering into BIM was highlighted as an unrealized potential of BMC. The interviewees ("AA", "AM") used examples from acoustics- and fire engineering. The fire and acoustics experts use drawings, mark walls with a felt-tip pen, and return this to the architect. This should instead be a BIM-based process, where fulfilment of requirements is verified in a BMC ("AM").

BMC as a service to the clients

BMC can also enable new services to clients. One of the architecture companies had developed their own rule-set and used this as part of the company's BIM project profile ("*AM*"). "It can be hard to sell out use of BIM to new clients. So, therefore we have established it as a general rule - as a "*company*" strategy and a "*company*" requirement - which all our models will go through our *company's BIM based QA check. This has been* developed with support from the Solibri vendor. One reason for this development was that rule checks report too many false errors.

"*It is easy to become a little discouraged when are too many red warning triangles. Based on this, we just picked out a few rules, some simple and some self-defined. This makes new clients aware of the potential – and their experience show that this is more fun to use than traditional drawings in project meetings*!" ("*AM*"). Competency in, and a methodology for, developing computable rules was requested by the practitioners. If the architects and engineers are to take expensive actions based on reporting from BMC, they must trust the foundations for the rules. Better rules are preferable to more rules.

Development of BMC is demanding

One of the interviewees ("*AO*") had started the development of their own rule checking solutions based on two Norwegian standards (NS11001, part 1 and 2) on accessibility. Their experience showed that this was a demanding process with many steps and challenges. One demanding step was the need to re-structure the regulation text. Another lesson learnt was that many rules are often needed to verify a single regulatory statement. The whole process was quite demanding and the project was never completed.

BMC for multiple sources of requirements

"We (the practitioners) have to check design according to national requirements, standards, industry requirements, client requirements, as well as company design standards and QA systems, to enable the final solution" ("*CE*"). This implies that rule checking is not about one rule fits all purposes. The practitioners (architects and engineers) deal with compromising different, and often conflicting, interests. A digital solution for checking may be a useful contribution to these processes. The checking solution does not need to be automatic, but it must be valid and reliable so one knows what has been done by BMC and what must be done by skilled practitioners ("*AO*").

Good models or good projects

The focus on an holistic view can be expressed by the following statement: "As an architect, I would say that the focus must be on the well-builtness of the actual building, and that we do not lose sight of that perspective" ("*AA*"). The focus on the real building and not the building model is further emphasized by: "…but the purpose of design is not about passing a particular test as we do not test anything in isolation. It is very much about the relationship, and how each single solution fits into a totality - that is the challenge." ("*AA*"). This statement highlights the perspectives of the practitioners on integrated procedures and multi-disciplinary collaboration. Technology is useful only as long it supports their current project.

Summary of practitioner's demand for development of BMC

Figure 3 uses the IDDS framework (Owen et al. 2013) to summarize the practitioners' expectations of priority in the future development of BMC.

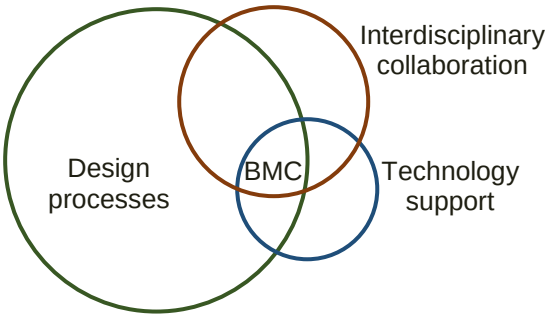

Figure 3 Summary of practitioners' demand for development of BMC

The practitioners' main focus was on how to perform their job as architects and engineers in the design of good solutions for the built environment. The development of high level of information in

BIM and the support of advanced BMC is not their primary objective, even if this is regarded as an important element for undertaking design projects. As illustrated in Figure 3, design processes are considered the dominating perspective.

Interdisciplinary collaboration is of high importance with respect to project coordination. Support of BIM and BMC do, in this respect, have an increasing influence on the visualisation and reporting aspects. In this case, clash detection features (based on simple geometrical rules) were the most used BMC functions for coordination purposes.

Technology support is currently limited to the coordination effort and clash detection. Therefore, it is the least important perspective as seen from practitioners' viewpoint.

4 Discussions

The intention of this study is to increase the awareness of missing aspects of BMC for the final building product. This can contribute to better utilization of available resources and an increase of multi-disciplinary research projects. This is not a comparative study to identify whether researchers or practitioners have the correct answer. However, combining both aapproaches may end up with a very holistic and balanced perspective implied by IDDS.

Use of IDDS as the framework and the assessment of the literature survey and feedback can of course be discussed. IDDS is a qualitative methodology for identifying relevant perspectives and their relation. The size and position or the three circles illustrating the perspective must not be interpreted as exact measurements, but as illustrations of profiles. The IDDS also represents a framework to explore and present drivers for change, enablers, barriers and opportunities, and to relate these factors to the short, middle and long term (Owen et al. 2013). This study is not a complete study utilizing all elements in the IDDS, and studies exploring these factors can be a foundation for further studies.

This type of study could be conducted by the use of multiple theories and frameworks for analyses of findings. The information science (IS) research community has a long tradition for exploring relations between technology and organisation at various levels. The IT for construction community should therefore search for support within IS related communities and their research traditions. Larsen et al. (2015) have collected and described 98 IS related theories. A challenge in this respect is to select relevant theories as foundation for development of BMC software

Studies by Hjelseth (2015b) document that interpreting codes into specifications for programing into software is a demanding process in itself. This type of development was also characterized as a multi-disciplinary domain combining construction, informatics and legal knowledge (Hjelseth, 2013). This indicate that the papers are developed within too limited projects.

The above discussions can give the impression that this type of research should be conducted by a multi-disciplinary research-team using a broad spectre of advanced theories and methods. However, IDDS as framework is an applicable way for researchers within the IT for construction research community to explore technology in relation to more "soft" and human related themes.

The findings illustrate a high and increasing activity within BMC and related themes. A literature survey by Dimyadi (2016) identified a) regulatory knowledge models, b) compliance audit systems and c) Building Information Models as the three themes with the highest number of publications. This study supports that the observations from the CIB W78 papers used in this are representative.

Proof of concept is a realization of a certain method or idea to demonstrate its feasibility, or a demonstration in principle, the purpose of which is to verify that some concept or theory has the potential of being used. A proof of concept is usually small and may or may not be complete (POC, 2016). This approach can contribute to making the theoretical research more applicable, but it may also contribute to defragmentation. It can therefore be challenging to build further upon other researchers' contributions, without having a framework. In this respect, it can be useful to distinguish between differences in approach and scope in research and development.

Rules are expressions of requirements. This can be specified according to national requirements, standards, industry or, client requirements, in addition to company design standards and QA systems. Dealing with QA is demanding, and studies by Kiviniemi (2005) document that initial requirements become lost during the design process. Use of BMC can support supervision with the various requirements, presupposed that it is easy to specify the rules in the BMC software. This case is also an example of the relation between technology and practical situations in practical design processes.

This study has been conducted on a limited number of papers presented at an IT related conference, and interviews were conducted with four very skilled practitioners. This does of course not give evidence to state clear conclusions of the research within this domain – nor to propose how it should be done. However, this study can be used to raise discussions about missing parts, and awareness of how much is actually on track in research.

Further research should not focus on the new technology alone, but rather on how to implement findings from this kind of study into a more holistic type research. In this respect, the CIB W78 community has started the development of a research road map for BMC (Dimyadi and Amor, 2016). The roadmap has incorporated a "Future Scenario" chapter that includes "Stakeholders' opinions on required/envisaged future systems, processes and technologies" and "Preferred future practices and skills". The "Research Agenda" chapter includes a section about "Cooperation between research and practice" (ibid.). This study confirms the importance of focusing on these perspectives in future work.

5 Conclusion

The expectations of BIM-based model checking (BMC) are very high in the AECOO industry. However, the extent of BMC use in real projects is hard to observe, except for coordination control based on the use of clash detection and reporting functionality. This is due to the unavailability of practical digital rules currently supporting the design processes. The development of BMC solutions to enable compliance checking against codes and standards, with a level of validation sufficient to replace the manual effort, remains a challenging undertaking. Compliance with codes and standards is a necessary step for the complete and final design, but only exercised once on the complete and detailed building model.

There is a limited support of BMC solutions during the briefing phase of the design process. Digital rules supporting the development of the "well-designed built environment", while also complying with formal requirements, is still missing. The development of BMC solutions should therefore be more oriented towards the projects stakeholders' needs. The practitioners' point of view and their need for various types of BMC related support is difficult to identify in research. Research has a high focus on advanced solutions, while practitioners need more support and implementation of practical solutions. Exploring practitioners' needs has identified "low hanging fruits" in relation to implementing industry's best practices as digital rules. Practitioners would prefer to have access to small dedicated checkers that can minimise or replace specific manual tasks accurately and reliably.

The research within BMC appears to be characterized by broken chains. Individual efforts in isolation lack cohesion and have a limited contribution to the overall scheme.

Using a theoretical framework from the information science is useful to position the contributions from research and development in relation to practitioners' needs. The development of a road map is an important effort to align with the increasing activity within BMC as a research domain. Applied research that focuses on the development of solutions to accommodate practitioners' demand instead of investing on advanced solutions will likely to win most implementations in the AECOO industry.

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