Case Study

Developing and Testing a Tool to Evaluate BIM Maturity: Sectoral Analysis in the Dutch Construction Industry

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Abstract: This study's objective was to evaluate the status of building information modelling (BIM) implementation within the Dutch construction industry by means of a developed BIM maturity tool that could be applied within the construction industry's various disciplines. Existing BIM maturity models tend to focus on technological aspects and have often been developed for specific disciplines. This paper first describes the development of a maturity model that enables the assessment of both technological and organizational aspects of BIM and enables comparison of all the disciplines in the construction supply chain. Second, the applicability of the proposed BIM maturity model is explored by using the model in in-depth interviews at 53 Dutch firms that represent the various disciplines within the construction industry. The output of the testing of the BIM maturity model shed light on the current implementation status of individual companies and, when aggregated, of the subsectors present. The latter information is valuable for sectoral associations because it identifies differences and similarities in BIM implementation across subsectors. The main finding is of strong strategic support for BIM among the leading companies evaluated. However, the formalization of BIM-related processes, tasks, and responsibilities is lagging behind BIM developments. Notably, respondents emphasized aspects related to people and culture when it came to implementing BIM, with awareness, education, and training regarded as essential elements in stimulating BIM maturity growth. Based on these findings, priorities have been identified to stimulate the BIM implementation process that can be included in sector-specific or industry-wide policies. **DOI: 10.1061/(ASCE)CO.1943-7862.0001527.** *© 2018 American Society of Civil Engineers.*

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Introduction

Building information modelling (BIM) has progressively received more and more attention since the beginning of this century because of its many promises including increased productivity, reduced failure costs, and new ways of collaboration (e.g., Eastman et al. 2011; Bryde et al. 2013; Eadie et al. 2013; Porwal and Hewage 2013; Miettinen and Paavola 2014). However, practice shows that projects cannot always take full advantage of these promised benefits. It appears that the inconsistent BIM maturity levels across collaborating parties in a project limit the degree to which BIM goals and accompanying expectations can be realized, especially regarding BIM uses with extensive data exchange between parties. Previous research has shown that an important factor in successful BIM use in a collaboration of multiple parties is the capabilities of the parties in terms of the desired or required BIM working methods (Adriaanse et al. 2010). The readiness of an organization, in terms of both soft and technical aspects, has a great influence on the extent to which it is able to leverage the potential of information technology (IT) (Alshawi 2007). In this regard, Dutch sectoral associations have also recognized that differing levels of BIM readiness within organizations representing the various disciplines within the Dutch construction industry is a serious implementation barrier to BIM supported collaboration between parties. Given this situation, they have called for a tool that could help them identify differences in BIM maturity levels, as well as the uses, drivers, and barriers among the subsectors. Using such a tool, the sectoral associations aim to receive inputs that could be directive in defining policies and measures to stimulate BIM from the sector's perspective. In addition, the BIM maturity tool could support individual organizations in identifying priorities for improving their BIM implementation process.

An initial observation is that the literature points toward a lack of a uniform BIM definition. Based on a literature review of BIM definitions, this study distinguishes the following elements as essential in describing BIM:

- an object-based definition of a construction and its elements (Eastman et al. 2011),
- cooperation between multiple disciplines across the different phases of a project (Miettinen and Paavola 2014),
- a life cycle perspective on a construction object (Gu and London 2010; Eastman et al. 2011; Miettinen and Paavola 2014),
- an information technology (IT) supported and consistent digital representation [in three dimensions (3D)] of a construction object (Gu and London 2010; Eastman et al. 2011), and
- a centralized consistent repository for all data related to a project or asset (Succar 2009; Gu and London 2010).

So, to sum up, BIM should be seen as an object-based and multidisciplinary approach aimed at facilitating collaboration between parties and the integration of object-related information over the entire life cycle of an asset. This function is supported by IT, through which building objects are often captured in 3D representations.

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The objective of this explorative study is to develop a BIM maturity model that is able to assess BIM maturity of organizations in the various subsectors of the construction industry while, in doing so, addressing all life cycle phases of a building object. The practical applicability of the developed BIM maturity model is tested by evaluating the BIM maturity of primarily leading firms that are active in the various subsectors of the Dutch construction industry.

This research focuses on BIM maturity at the organizational level. Aggregating the results to the sector level provides insight into the current BIM maturity of organizations in the various subsectors and their similarities and differences. This reveals the current opportunities for and barriers to BIM cooperation between parties of these different subsectors. The results of this explorative BIM maturity sectoral study provide the construction industry and its specific subsectors with recommendations on how to increase and improve BIM use.

This article starts with a review of existing maturity models on BIM implementation and use. Based on this review, a generic model for assessing the BIM maturity level of a firm in the construction industry is developed. Following this, a methodological justification and a design for the empirical research is provided. In the next section, the developed BIM maturity model is assessed in 53 in-depth interviews of firms in the Dutch construction industry. Based on the development and testing of the BIM maturity model, the main findings are discussed, followed by conclusions and managerial implications.

Assessment of Existing Maturity Models

Several existing maturity models were assessed to determine their applicability for the proposed BIM maturity research. In this assessment, four categories of requirements for design-oriented research have been applied (Verschuren and Doorewaard 2007):

- Functional requirements comprising the features that the artifact has to fulfill. These requirements have been matched with the scope of the BIM maturity research, including the evaluation of collaboration along the entire supply chain, appropriateness to all the disciplines in the construction industry, appropriateness to the Dutch construction industry, and evidence of a life cycle perspective.
- Contextual requirements covering political, economic, social, and transactional requirements from the environment. These requirements take account of the individual organization being part of a chain of collaborating parties in a dynamic context. The requirements are based on the adopted BIM definition, the intended added value of the model in the assessment, and mutually comparing results across disciplines.
- User requirements comprising requirements from current and future users of the model. These requirements are based on a stakeholder analysis and use scenario, including primarily the perspective of individual organizations.
- Structural requirements covering the tangible and intangible characteristics necessary to fulfill the requirements of the other three categories. These requirements originate in the starting points of BIM maturity research, building on the existing scientific knowledge with a strong emphasis on the usability for the target users.

The evaluated maturity models are the BIM Capability Stages and the BIM Maturity Matrix (Succar 2009), the BIM Quickscan (van Berlo et al. 2012) of the Netherlands Organization for Applied Scientific Research (TNO), the National BIM Standard (NBIMS) Capability Maturity Model (National Institute of Building Sciences 2012), iBIM maturity (Bew et al. 2008), Penn State BIM assessment (Computer Integrated Construction Research Program 2013), the BIM proficiency matrix (Indiana University 2009), the Supply Chain Management Process Maturity Model (Lockamy and McCormack 2004), and the Capability Maturity Model integration (CMMi) (Software Engineering Institute 2010).

A multicriteria analysis indicated that none of the existing maturity models fully satisfied the objectives of our BIM maturity research (see the outcomes of the qualitative assessment in Table 1). The rationale behind the multicriteria analysis is based on the requirement categories for design-oriented research of Verschuren and Doorewaard (2007) as explained previously. The following findings illustrate the need for a new BIM maturity model:

1. Collaborative aspects receive little attention in the models assessed, especially in terms of collaboration within the construction supply chain. This is despite organizations with different BIM maturity levels collaborating intensively in a project. Only the Supply Chain Management Process Maturity Model (Lockamy and McCormack 2004) fully addressed this criterion, with that model especially developed to evaluate interfirm processes.
2. Complex frameworks are often applied and maturity assessment results are unclear or not transparent, i.e., interpretation and mutual comparison of maturity results is hindered by ambiguous scores or lacking foundations. Consequently, the outcomes of the various maturity analyses are not mutually comparable. This reduces the usability of the BIM maturity models as supportive tools for organizations and sectoral associations.
3. The meaning and requirements for the various maturity levels are often poorly defined and ill-founded in the related literature. In general, the development and design choices made have been poorly explained, a failing which was also identified by Liang et al. (2016). As such, the background required for appropriate measurement is lacking, and ranking an organization according to a maturity model, such as when determining whether maturity has increased, is challenging.
4. Existing models pay insufficient attention to organizational processes and instead tend to focus on technological characteristics of BIM.
5. Many of the maturity models focus on the evaluation of specific disciplines (e.g., clients) and this limits their applicability by different disciplines within the construction industry.

Based on the aforementioned shortcomings and limitations of existing maturity models, the potential benefit of a new BIM maturity model was evident. Although none of the assessed maturity models fully satisfied the requirements, many contained strong elements that were brought together in the new BIM maturity model. Based on the assessment in Table 1, the CMMi framework was chosen as the general framework for the new BIM maturity model. The major reason for this is that the CMMi focusses on process areas that can constitute best practices and that can be tailored to appropriate BIM criteria and BIM uses for the construction industry. Moreover, the CMMi aims to cover all the life cycle phases, which fits very well with the adopted BIM perspective and the different subsectors involved in the construction industry. Additionally, the CMMi structure makes it possible to include aspects of other maturity models such as the collaborative aspects of the Supply Chain Maturity model and the clear presentation of both maturity model descriptions and outcomes found in the Penn State Maturity model.

Developing a New BIM Maturity Model

In this section, the two basic dimensions of the maturity model developed are discussed. First, the general descriptions of the

Table 1. Assessment of existing maturity models

Requirement type	Requirement description	Maturity models								
		BIM Capability Stages	BIM Maturity Matrix	BIM Quickscan	NBIMS Capability Maturity Model	iBIM maturity	Penn State BIM assessment	BIM Proficiency Matrix	Supply Chain Management Process Maturity Model	Capability Maturity Model Integration
Functional requirements	The model was developed or is suitable for the Dutch construction sector	P	P	S	P	P	P	P	N	N
	The model has been developed in order to measure BIM maturity level	N	S	S	S	S	S	N	N	N
	The model can be used at sector, corporate, and project levels	N	S	N	N	N	P	N	P	S
	The model can be applied in organizations of different sizes	S	S	S	S	P	P	S	S	S
	The different BIM maturity levels are construction-specific and distinctly defined	N	N	N	P	P	P	N	N	N
	The model covers different phases in the life cycle of a construction work (and the parties involved)	N	N	N	N	N	N	N	N	P
	The model is able to test the maturity level of BIM applications	N	N	N	N	N	P	N	N	S
Contextual requirements	The model covers BIM-supported cooperation between parties	P	P	N	N	N	N	N	S	N
	The results of the model offer insight into the appropriateness of possible project partners and can be communicated	N	N	P	P	N	N	N	N	P
	The model can be adapted to future BIM applications (best practices) and other relevant developments	N	N	N	S	N	P	N	N	S
User requirements	The maturity audit is complete and clearly described; the results are not heavily reliant on the interpretation of the auditor/interviewer	N	N	S	S	N	S	S	N	S
	The maturity audit can be carried out within the limited time of an interview or survey	N	N	S	S	P	P	N	P	P
	The results of the maturity audit are transparent and understandable	S	N	S	N	N	S	S	P	S
	The outcome of the maturity audit provides sufficient understanding of the current phase of BIM implementation	N	P	N	S	P	P	N	N	N
	The maturity model provides a clear path from a lower to a higher maturity level	N	S	N	S	S	S	N	S	P
Structural requirements	The maturity model has a sound scientific basis	S	S	N	P	S	P	P	S	S
	Software for execution or visualization of the maturity analysis is generally available (e.g., MS Office)	N	N	S	S	N	S	S	N	P

Note: S = requirement satisfied; P = requirement partly satisfied; and N = requirement not satisfied.

maturity levels are provided. Second, the six main criteria in the maturity model are explained.

Description of Maturity Levels

In order to further detail the generic maturity definitions contained in the CMMi, the findings of the Standardised Process Improvement for Construction Enterprises (SPICE) project were considered. This project examined the applicability of the CMMi methods for the construction industry and concluded that construction supply chain relationships are insufficiently covered (Sarshar et al. 1999). Furthermore, it was concluded that improvements were required in the maturity definitions if they are to serve the vast diversity of organizations within the construction industry in terms of organizational size, focus, and financial position. In addition, it has been argued that a maturity model cannot be operationalized unless criteria are defined that reflect the context of the specific sector (Vaidyanathan and Howell 2007). Considering the aforementioned aspects, the definitions of Siriwardena et al. (2005) and of Lockamy and McCormack (2004) have been used in further specifying the five maturity levels of the CMMi. Here, one should also note that although Vaidyanathan and Howell (2007) described four specific levels for a construction supply chain maturity model, these can, for the most part, be matched with the definitions of Lockamy and McCormack (2004). The contributions from these various publications are combined to come to the descriptions of the five maturity levels used in the newly developed BIM maturity model as shown in Table 2. A distinction is made between internal and external processes in order to make supply chain aspects more explicit.

The general descriptions of maturity levels in Table 2 have been further specified for the context of the criteria used in the BIM maturity model. Explanations for the developed criteria and subcriteria can be found in the following.

Criteria and Subcriteria Used in the BIM Maturity Model

A building information model can be thought of as an information system and as part of the organizational context. It is not an isolated system, but forms part of a larger whole. The information system is

Table 2. Definition BIM maturity levels

Level	Internal definition	External definition
0	Processes related to the criterion are not present in the organization and no related goals are formulated.	—
1	Internal BIM processes are not defined or limited and ad hoc. Good practices are not shared or laid down in procedures (no multiproject integration). Performance of BIM-related processes and projects is unpredictable and completely dependent on skills in the project team.	Cooperation between companies within a project is ad hoc and reactive rather than proactive. The organizational structure and functions are not geared to collaboration within the supply chain (no multifirm integration). Performance of BIM-related external processes and projects is unpredictable and targets are often not met.
2	BIM policies and procedures have been established for the management of major project-specific BIM processes, whereby good practices can be repeated and processes become more predictable. The structure of the organization is traditional and has not adapted to the BIM process. BIM processes are followed, adjusted, and evaluated to a limited extent during the project.	The importance of cooperation in the supply chain is recognized through the definition of objectives and external fundamental processes. However, the organization has changed insufficiently to reflect supply chain processes. Although external BIM processes are better able to predict, objectives are often still not met.
3	BIM goals are formulated by management with strategic intention, and there is a good overview of the performance and progress of BIM projects. Organizational structures, job profiles, and working methods are defined in accordance with BIM-related tasks, providing greater understanding of the delivered quality of projects. Good BIM practices are documented and applied as standard processes throughout the organization. Based on trust and motivation, there is increasing unity regarding joint BIM targets, which outweigh possible frustrations.	At this level, a breakthrough takes place with regard to cooperation in the supply chain: organizational structures and functions are partly focused on supply chain management, whereby joint supply chain goals and activities can be set. Clients/partners in the chain are involved in efforts to process improvements, leading also to greater mutual satisfaction.
4	Measurable quality targets (quality programs) are made with regard to the outcome and progress of processes. BIM processes are controlled objectively, enabling adjustment and helping to keep targeted performance within acceptable limits. Risks associated with new, more advanced BIM applications can be controlled due to the strong process discipline and the acquired skills. Both the internal culture (in which confidence in the BIM approach and method is present) and the satisfaction of the project partners strengthen the competitive position/authority of the organization.	Cooperation with chain partners is part of the business strategy and takes place on the process level, including joint efforts on process improvement. Traditional functions disappear at the expense of functions and procedures focusing on external processes in the supply chain. This enables more-advanced applications to be set up together with supply chain partners, such as joint planning for both the short and the longer term. This cooperation, with shared confidence in the objectives, becomes a competitive advantage.
5	Effective evaluation of processes and projects contributes to continuous learning and improvement. Internal processes are aligned with the collaboration within the supply chain. Data on the effectiveness of processes are used to analyze new technologies and proposed changes in organizational processes. Through this increased understanding of the processes, organizations are able to assess and implement large-scale process changes. The corporate culture stands for openness and transparency for the sake of intensive collaboration.	An organization operates as part of a *multifirm* supply chain. This is characterized by intensive cooperation with supply chain partners in which BIM processes are continually improved. This cooperation is ensured by the strong mutual trust and financial dependence. The exchange of performance data makes it possible to anticipate problems and to implement new BIM applications/technologies. Evaluation of processes and projects contributes to coordinated learning across projects.

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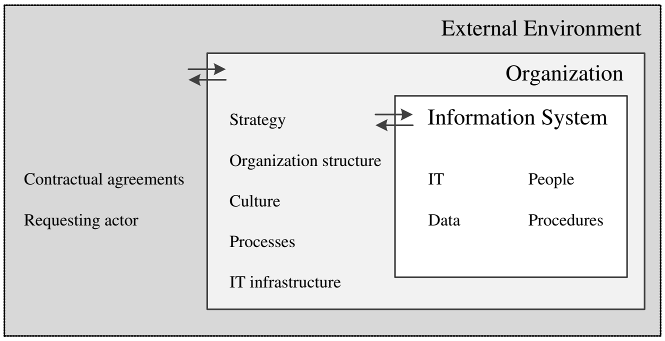

Fig. 1. Information system and its interaction with the organization and the environment. (Adapted from Silver et al. 1995.)

characterized by a number of subsystems: hardware, software, data, people, and procedures (Silver et al. 1995). These subsystems are closely related with each other and jointly determine the functioning of the information system. However, as part of the organizational context, the information system is not self-contained but is a part of a larger whole. Silver et al. (1995) describe other aspects of the organization that interact with the information system, such as business processes, strategies, culture, organizational structure, and IT infrastructure. Note that new or existing information systems, for example in the area of planning, calculation, enterprise resource planning (ERP), asset management, or geographical information systems (GIS), can either be integrated with BIM or can be used as separate IT systems. In addition to the information system and the organization, influential factors from the external environment can be distinguished. The external environment affects the motivation to develop and use information systems, which can originate from contractual agreements (Adriaanse 2007). The information system, with its internal and external interactions, is shown in Fig. 1.

Since aspects of the information system, of the surrounding organization, and of the external environment represent the interactions and determine the performance of that information system, they are seen as appropriate criteria for inclusion in a BIM maturity model. In the following, the criteria included in the maturity model are explained further.

Based on the elements of the information system, a framework has been constructed with criteria that are used to define *BIM maturity* (the domain). Some criteria overlap and can be merged into a single criterion. In doing so, aspects related to people and to culture are included as a single criterion, and aspects of the IT infrastructure and information and communications technology (ICT) are similarly combined. The data and documents that are part of the IT infrastructure constitute an important BIM aspect, and these are therefore separated out as a separate criterion. Most criteria are broken down into several subcriteria to distinguish and assess the specific aspects within each criterion. These subcriteria are based on the descriptions of criteria in the literature (Silver et al. 1995) and criteria used in existing maturity models, with significant contributions from the Penn State BIM assessment (Computer Integrated Construction Research Program 2013) and the Supply Chain Management Maturity Model (Lockamy and McCormack 2004).

The BIM maturity model is divided into six main criteria, namely strategy, organizational structure, people and culture, processes and procedures, IT (infrastructure), and data (structure). Most criteria include several subcriteria (Fig. 2). No particular weights are allocated to the criteria, allowing a uniform comparison of the criteria scores. Considering organizations with varying focus areas

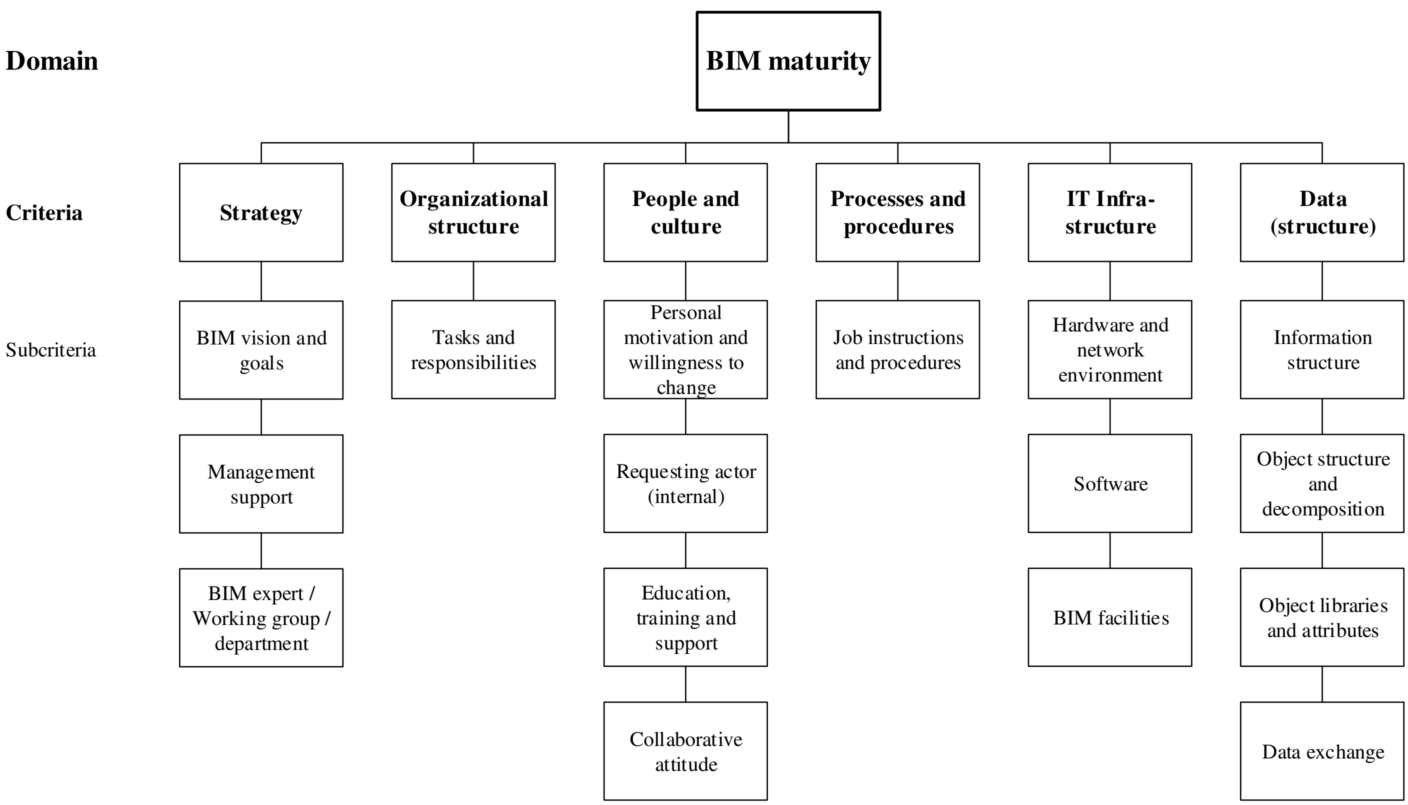

Fig. 2. Criteria and subcriteria of the BIM maturity model.

or BIM use scenarios, this uniform model structure allows organizations to set priorities afterwards.

In the following subsections, the criteria included in the BIM maturity model are explained in the context of BIM. In doing so, justifications for the chosen subcriteria are presented (see also Fig. 2).

Strategy

BIM is often included in an organization's strategy. It can be a key element in a marketing or production strategy, or even the core of a strategy. If the intentions of the digital information model do not align with the organization's strategy, the implementation and use of BIM can fail. The strategy should be based on the mission and goals of the organization. More specifically, a specific *BIM vision* and associated *goals* should be aligned with the organizational strategy and vice versa. The implementation of the strategy, however, requires sufficient *management support*, both in spoken words and by management committing financial and other resources for short- and long-term planning. Further, dedicated time and expertise from a *BIM expert/working group* are indispensable elements when it comes to the operationalization of the BIM strategy.

Organizational Structure

Aspects of the formal structure of the organization, such as the division of labor and associated power, are formalized in job descriptions, which contain the *tasks and responsibilities* of the employees. Due to new BIM-related processes, new working methods, new roles within the organization and the project, and new competences with regard to the use of, for example, BIM software, a revision of the traditional tasks and responsibilities is required. To what extent an organization has adopted new, or updated, tasks and responsibilities, for example by means of changed job profiles, reflects the ability of its staff to support the BIM processes. Further, the authors recognize a strong relationship with softer aspects in the field of organizational change, and these are explained next as part of the *people and culture* criterion.

People and Culture

This criterion is composed of a set of basic assumptions and habits that are anchored in an organization and which will be transferred to new employees. These facets determine the *personal motivation* for working with BIM and expanding its use into new areas. Such motivation can spring from the many benefits that BIM offers an organization, although these will generally not directly affect the entire organization. Therefore, it is important to have a BIM champion for the implementation process, one who functions as an internal *requesting actor* for the application of BIM. In addition to being motivated to work with BIM, the functioning of BIM is also determined by having the *competence* required to be able to work with it. An organization should therefore provide intensive *education and training* to all those who are part of the BIM process. The culture of the organization also affects the openness (to external partners) and the *degree of collaborative attitude* or orientation toward the supply chain. Achieving an integrated and multidisciplinary BIM approach requires a setting and an attitude that are aimed at cooperation. To this end, the organization needs to show a *willingness to change* its traditional culture, structure, and processes.

Processes and Procedures

A process can be defined as a collection of related activities aimed at a specific result or output. It is important, in this context, that the processes contribute to the desired functioning of BIM and vice versa. The consistency and the performance of processes depend on the extent to which these processes are formalized in *job instructions and procedures* (e.g., with regard to various BIM uses). Job instructions are seen as detailed step-by-step acts or practices, compared with procedures that provide a set of guidelines for streamlining processes.

IT Infrastructure

The technical means within the information system, initially consisting of the (BIM) *software*. In addition, the IT infrastructure includes the *hardware and network environment* that support smooth use of the software as well as the sharing of data. The quality of the network environment determines the extent to which project disciplines can work in an integrated way and in real time. Another component is the *BIM facilities*, such as spaces where the models can be visualized. These facilities enable interactive coordination sessions with project partners, for example to detect clashes.

Data (Structure)

This criterion refers to the management, structuring, (re-)use, and exchange of project-related information. First, it is important to store project data in a structured way and for other people/parties to be able to access these data. This *information structure* can be facilitated by a document management system. Next, an object-oriented approach constitutes the core of the BIM definition. The basis of this is formed by drafting an *object structure and decomposition* (possibly in combination with systems engineering), and using unique codes for all the objects in the model/project. Depending on the intended uses of BIM, *object libraries* can be helpful in standardizing and easing the BIM model design processes. Specifications and characteristics of objects can be linked by means of attributes, possibly included in object libraries, or otherwise added to objects in the model. Integration with models of supply chain partners is determined by data exchange regarding object information, discipline-specific models, or merged models.

Method and Data Collection

A BIM maturity model, which is visualized as a matrix, that enables the measurement of organizational BIM maturity has been developed. The horizontal axis of this matrix consists of the maturity levels, whereas the vertical axis consists of the criteria and subcriteria outlined in the previous section (an illustrative example of the matrix is presented in Table 3). Subsequently, this matrix was

Table 3. Illustrative example of the maturity model: subcriterion BIM vision and goals

Maturity level	Description maturity levels of subcriterion BIM vision and goals (part of strategy criterion)
0 = Not present	No vision or goals for BIM formulated.
1 = Initial	A basic vision for BIM is defined, but there are no concrete goals associated with it.
2 = Managed	There are general BIM goals, but a BIM vision is lacking or not kept in line with the broader strategy.
3 = Defined	The BIM vision fits within the broader organizational vision/ strategy and is aligned with partners.
4 = Quantitatively managed	SMART BIM goals are defined.
5 = Optimized	The BIM vision and goals are actively monitored (e.g., by means of periodic reporting) and, if necessary, updated.

Note: SMART = Specific, Measurable, Achievable, Relevant and Time-bound.

translated into an interview format to enable data to be collected through in-depth interviews to enable its completion. More than 50 interviews were conducted in 2014 and 2015. Interviews were held with representatives of organizations drawn from seven subsectors: clients and owners; architectural firms; engineering firms; commercial and industrial building contractors (CIB); civil structure contractors; mechanical, electrical, and plumbing (MEP) contractors; and suppliers.

The measurement tool uses a *strict step* principle when determining the maturity level of each criterion, i.e., all the elements of a certain maturity level description must be met before moving on to the subsequent level. For example, a company will be evaluated as having a maturity of Level 2 on a given construct if not every aspect of Level 3 is met, even if all the criteria for Levels 4 and 5 are met. This approach highlights to a company those actions that should be taken and, as such, offers them a gradual path to growth.

The research project included a supervisory group, consisting of representatives from all distinguished subsectors, that was able to provide a list of firms that were appropriate and could be approached to participate in the research. Besides the willingness to participate in the research, no specific criteria were used to select the firms and their respondents. Factors like organizational size of the firm or age and experience of the respondent have not been evaluated in the selection process, nor in the evaluation of the outcomes. However, the initial approaches to respondents found that organizations with limited focus and experience of BIM were often unwilling to participate in the research. As such, the interviews that did take place tend to provide insight into the BIM maturity of those companies that are leaders in the industry. Therefore, the results of the research should not be seen as providing a general representation of the construction industry as a whole.

Nevertheless, interviewing leading firms could still show the trend in the development and adoption of BIM. In addition, they can highlight drivers and barriers they experienced in earlier phases of the BIM implementation process. This information can be very helpful for companies that are at these lower BIM maturity levels and may be struggling with certain barriers.

Table 4 provides an overview of the number of companies interviewed in each subsector. The selected companies varied in size, with both small and medium enterprises (SMEs) as well as large companies included in order to reflect the wide diversity of companies in the construction industry. Moreover, companies from the two main divisions of the construction industry, commercial and industrial buildings, as well as the infrastructure subsectors were included. Using a standard interview format, a total of 53 interviews were conducted. Given the commercial value and confidentiality of the information provided during the interviews, the results are presented anonymously. The participating organizations were either interviewed face to face (55%), through Skype (15%), or by phone (30%). The respondents consisted of employees and executives who held a broad overview of the BIM developments within their organization and who often also had a clear picture of BIM developments at other parties in the construction supply chain.

Generally, approximately two hours was required for each interview, although the duration varied depending on the knowledge, experience, and comprehensiveness of the answers provided by the respondents. To assess the BIM maturity level for the various criteria, the interview format was partly open-ended, allowing the interviewer to explore areas that were revealed during the discussion. When required, the researchers would ask the interviewees to provide additional documentation to support the given answers. Following the round of interviews, data analysis was performed in three steps. First, after a visit, a researcher would prepare a BIM maturity report for that company. Second, to achieve construct validity, these draft reports were submitted to the respondents for verification. After the verification and integration of comments, the final BIM maturity report of each organizational assessment was compiled. Finally, when all 53 assessments were completed, the overall results were analyzed. The data were first analyzed by subsector so that trends, and similarities and differences, between subsectors could be revealed. Next, aspects of BIM were analyzed for the entire data set to investigate the development of BIM within the Dutch construction industry as a whole. These results are presented in the next section.

Table 4. Number of interviewed organizations per subsector

Subsectors	Number of interviews
Clients and owners: (semi-)governmental organizations and housing associations	7
Architectural firms	6
Engineering firms	9
Contractors of commercial and industrial buildings	8
Contractors of civil structures	8
MEP contractors	7
Suppliers	8
Total	53

Results of the BIM Maturity Assessment Interviews

This section describes the results of the sectoral BIM maturity analysis in the Dutch construction industry, which involved assessments at 53 primarily leading companies in the field of BIM. The results of the BIM maturity sectoral assessment are presented in terms of the six main criteria of the maturity model: strategy, organizational structure, people and culture, processes and procedures, IT (infrastructure), and data (structure). Indications of the BIM maturity level for each subsector are provided. From these results, the adoption characteristics and priorities for further implementation of BIM in a front-running country can be identified.

Strategy

The main criterion, strategy, is made up of three subcriteria: *BIM vision and goals*, *management support* (both financial support and promoting the importance of BIM), and *BIM expert/working group/department*. The scores on the strategy criterion and its subcriteria are relatively high in all the subsectors (Fig. 3).

The lowest maturity score was found for the suppliers subsector (an average maturity level of about 2). This is reflected in the drivers of BIM implementation that were mentioned by the suppliers. Indeed, the interviewed suppliers experienced little intrinsic motivation and indicated that BIM had largely been adopted because of requests from their clients (particularly construction companies as the main contractor in a project).

On the other hand, the highest scores were obtained by the commercial and industrial building companies and engineering firms, with a BIM maturity score of around 4. These organizations generally had management that recognized the importance of BIM and that took initiative to stimulate awareness of the value of BIM. Moreover, these companies have specified a BIM vision, and accompanying goals, for both short- and longer-term strategic planning, and progress is monitored and measured over time.

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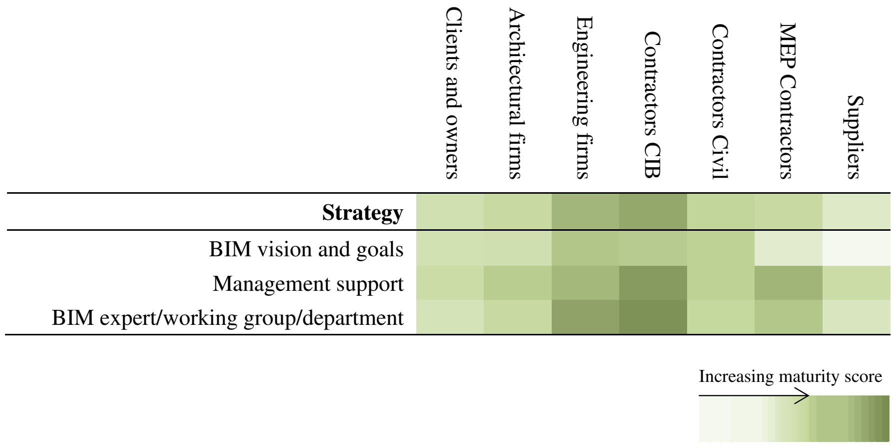

Fig. 3. BIM maturity scores of subsectors on strategy. CIB = commercial and industrial building contractors.

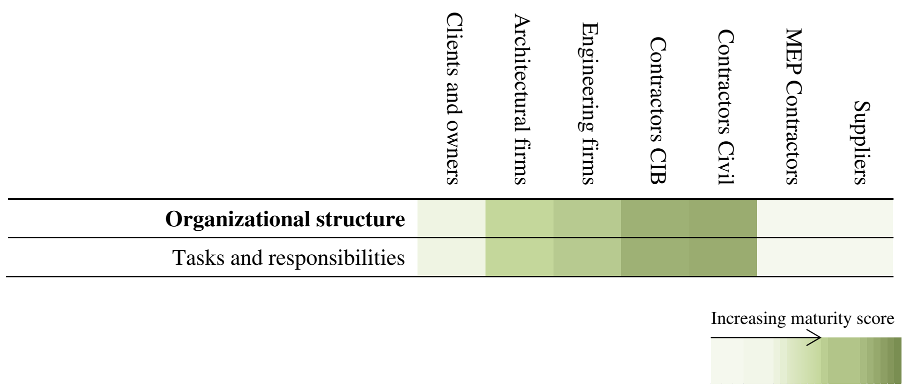

Fig. 4. BIM maturity scores of subsectors on organizational structure.

Organizational Structure

The organizational structure criterion consists of *tasks and responsibilities* and does not include further subcriteria. This criterion is assessed by asking the organizations' representatives about the extent to which tasks and responsibilities in the organization have been aligned with BIM use. In general, the scores on this criterion were relatively low when compared to the average maturity over all criteria. The majority of the interviewed organizations did not formalize changes in tasks, responsibilities, or job profiles as a consequence of modified BIM procedures. Rather, they tended to see BIM as an additional tool within existing roles and responsibilities, for example to support the design process (Eastman et al. 2011).

Of all the subsectors, architectural firms were clearest in the use of BIM as a supplementary tool. From their perspective, further adoption of BIM would not affect their designing processes considerably. As such, the implementation of BIM does not require a considerable revision of their formalized task descriptions. Conversely, many of the contractors did view BIM as a new way of working that should be streamlined using appropriate job profiles. They also recognized the value of role descriptions, which can be used to formalize tasks and responsibilities between different individuals, disciplines, and parties in a project. However, BIM-related roles had yet to be directly linked to the internal job descriptions of the employees concerned.

Despite the general awareness of this need, the formalization of tasks and responsibilities seems to lag behind the actual adoption of BIM. It should be noted, however, that many organizations are still in the early stages of BIM implementation and, therefore, BIM may only be being applied in parts of some projects. The need to formalize modified tasks and responsibilities may have been recognized, but it was not being prioritized. Rather, the respondents tended to put their emphasis on BIM operationalization and put their effort into extending BIM use into new areas.

As can be seen in Fig. 4, the highest scores for the organizational structure criterion were found for contractors of commercial and industrial buildings and of civil structures, whereas the lowest scores were found for MEP contractors, suppliers, and clients/owners.

People and Culture

The people and culture criterion is made up of four subcriteria: personal motivation and willingness to change; requesting (internal) actor; education, training, and support; and collaborative attitude. Those organizations that had an above average overall BIM maturity score often emphasized that this criterion was the most challenging in their BIM implementation process—that technical aspects can often be solved, but changing people is a complicated and gradual process. They saw it as important to work on boosting awareness and making clear how BIM can help facilitate, speed up, or professionalize people's work.

As shown in Fig. 5, the interviewed suppliers and MEP contractors scored relatively low for the people and culture criterion. They

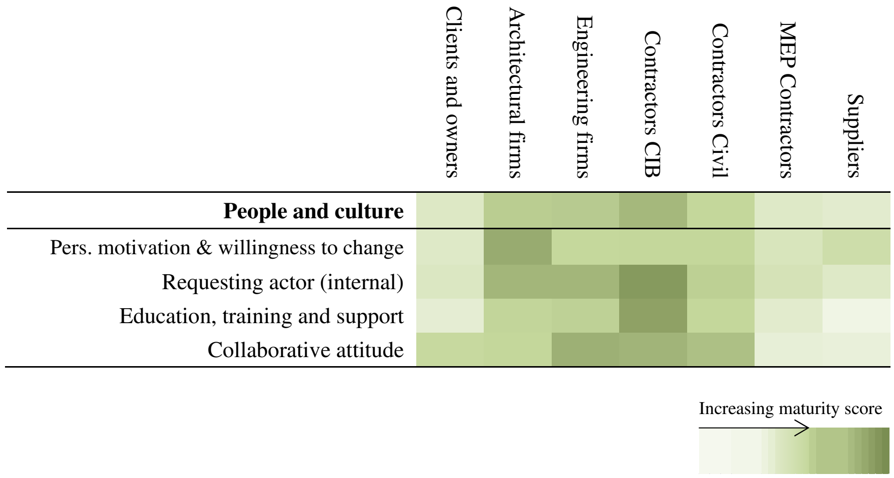

Fig. 5. BIM maturity scores of subsectors on people and culture.

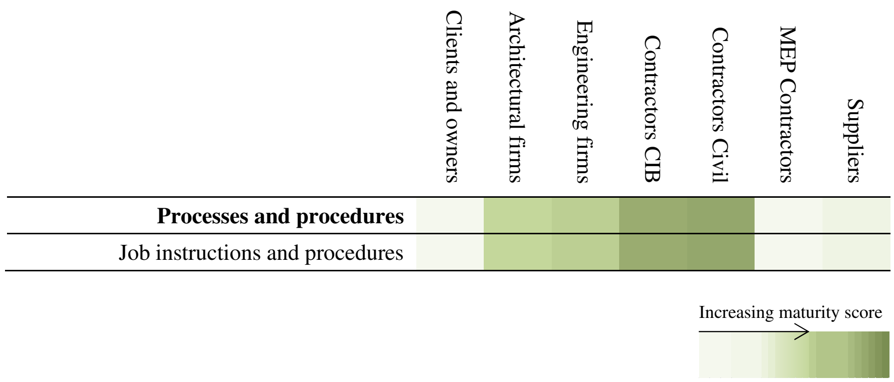

Fig. 6. BIM maturity scores of subsectors on processes and procedures.

saw too few benefits of BIM for their own work. In their experience, the efforts and investments they would have to make in order to join the desired BIM working method within a project often outweighed the expected benefits.

Clients and owners also scored below average for the people and culture criterion. It appeared that, besides cultural aspects, their organization's limited education and training with regard to 3D-oriented BIM applications also depressed their scores. Indeed, interviewed clients and owners stressed that they do not need to work with the 3D component of BIM. On the other hand, their focus within BIM is more on its uses related to maintenance during the operation phase of an asset, making the information attached to objects in the building model particularly important.

Processes and Procedures

The main processes and procedures criterion consists of *working instructions and procedures* and this factor does not include further subcriteria. The results on processes and procedures match those for the roles and responsibilities (organizational structure) criterion. Indeed, in terms of processes, there is a similar lack of formalization in terms of working instructions or procedures. The results (Fig. 6) indicated that the interviewed construction companies, both contractors of commercial and industrial building as well as contractors of civil structures, obtained the highest maturity scores (average just above maturity Level 3), followed by engineering companies and architectural firms.

IT (Infrastructure)

The IT (infrastructure) main criterion is made up of three subcriteria: *hardware and network environment*, *software*, and *BIM facilities* (such as projection screens or rooms equipped for BIM cooperation). The results of this criterion are shown in Fig. 7. Despite their often-lengthier experiences with 3D design software and a strong dependence on 3D software packages in their design work, architectural firms did not have the highest maturity scores for the IT (infrastructure) criterion. This seems to be partly due to their tendency to judge the IT (infrastructure) maturity against higher standards or envisioned state-of-the-art usage. As a consequence, requirements and expectations regarding BIM software are increased. In addition architectural firms were very able to identify shortcomings regarding software. Some of the interviewed architectural firms stated that they stay in regular contact with software vendors to discuss certain defects in functionalities. This information can be used in software updates.

In addition, the software aspect was generally given a reduced score due to limitations in the area of information exchange using open standards, such as the Industry Foundation Classes (IFC). Respondents who had experience with IFC indicated that IFC

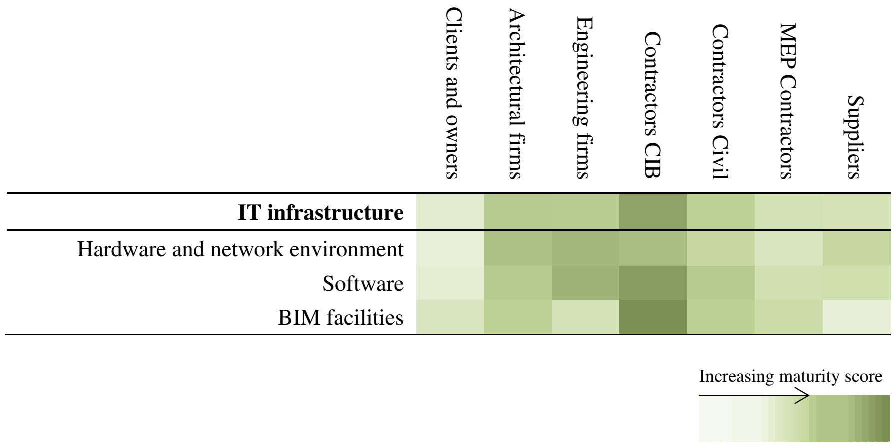

Fig. 7. BIM maturity scores of subsectors on IT infrastructure.

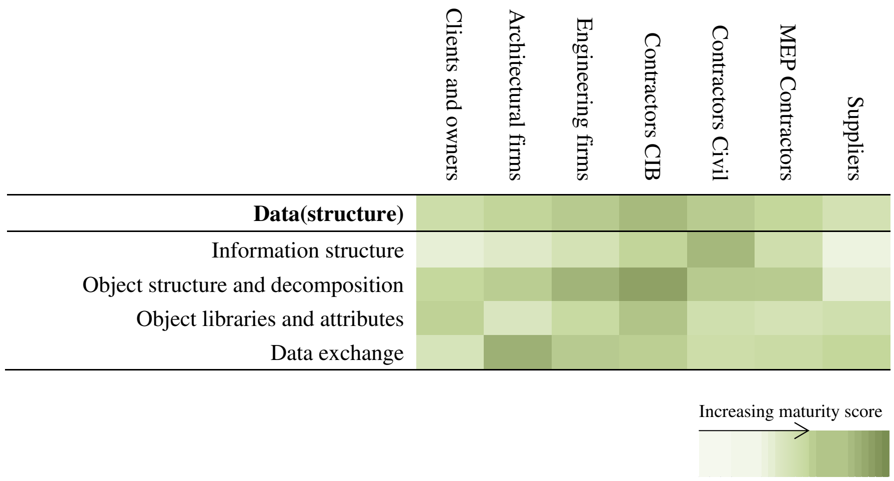

Fig. 8. BIM maturity scores of subsectors on data (structure).

exports sometimes lose building model data and therefore have limited reliability. The data exchange aspect is investigated in more detail within the data (structure) criterion.

With regard to the hardware and network environment, respondents indicated that initial investments, for example for the purchase of new laptops, are generally not a problem since the purchase of suitable hardware usually coincides with the decision to invest in BIM. Most parties are happy to make these initial investments in order to kick-start and accelerate the implementation of BIM. Management recognizes that the initial investment can be significant, but that it does not result in structurally higher costs. Moreover, the expected positive return on investments in the longer term is seen as a sound basis for justifying the initial investments. However, respondents did mention that the IT infrastructure, the data lines and servers, were often insufficient to handle rapidly the very large (and increasing) volume of data. Many of the contractors noted that this issue was particularly problematic at remote project locations with temporary facilities.

Most parties felt they were able to facilitate meeting/coordination sessions with BIM screens using beamers or smart boards. The parties earning an above-average maturity score had often invested in specific changes to work spaces and meeting rooms, for example by creating rooms where several project parties can cooperate. Commercial and industrial construction companies scored highly on this aspect: they attach considerable importance to 3D coordination (especially clash detection and coordination of disciplines) and have equipped meeting rooms and project rooms to meet these requirements.

Data (Structure)

The main data (structure) criterion is made up of four subcriteria: *information structure*, *object structure and decomposition*, *object libraries and attributes*, and *data exchange*. In general, the maturity scores of the various subsectors are similar; mostly with levels between 2 and 3 (Fig. 8). First, considering information structure, it emerged from the interviews that many parties do not use a document management system for storage and accessibility of project information, or if they do, they do not use it consistently. Respondents acknowledge that this aspect should be higher on their priority list, recognizing that a structured document management system can be linked more efficiently to objects in the building model. Such a link between the BIM environment and the document management system has been realized by more than half of the civil structure contractors whereas, in other subsectors, this seems very sporadic.

In terms of object structure and decomposition, it appeared that many organizations do not have a unified approach in place. From the interviews, the impression gained was that contractors of civil structures had taken a leading role in the use of a uniform structure/decomposition of objects, often originating from an adopted systems engineering approach. As seen earlier when it came to the formalization of tasks and responsibilities, suppliers again clearly had reservations: they often just follow the structure and methodology used and provided by their principal (main contractor). They see this as reflecting their position in the construction supply chain and a desire to act as flexibly as possible.

Addressing the next subcriterion, some of the interviewed parties stated that they had chosen not to have a uniform library of 3D objects, but to develop separate libraries on a project-by-project basis for the various software packages used. Transferring developed object libraries from project to project is mostly done on an ad hoc basis. Some organizations do create and maintain an object library at the organization level, but aligning or exchanging these libraries with supply chain partners is still rare. Explanations offered in the interviews included the diversity of software packages and the lack of well-implemented standards.

Finally, further addressing the object libraries, the respondents from the architectural firms explicitly mentioned the lack of available online object libraries of prefabricated or standard products from producers and suppliers. They see such libraries as being an important step toward further increasing automation and efficiency in the design and engineering processes. Moreover, this could enable detailed information on the manufacturing processes to be included during the early stages of the design, reducing the number of later change orders and clashes.

Discussion

In this section, the results from the BIM maturity sectoral analysis will first be discussed. Second, the BIM maturity model, including the interview instrument, will be evaluated. This will reveal directions for further research and, specifically, potential refinements to the BIM maturity model.

Evaluation of BIM Maturity Results

The BIM maturity of organizations is evaluated on the basis of several criteria. Fig. 9 shows the BIM maturity of the interviewed organizations by subsector on each main criterion. Some of the most notable outcomes are then discussed. Organizations in the construction industry as well as sector associations can use these outcomes to set priorities for further adoption and implementation of BIM. When interpreting the findings, one should not forget that only a limited number of organizational representatives were interviewed.

Almost all of the subsectors distinguished scored highly on the strategy criterion. This implies that the management of organizations attaches value to BIM development by setting an organizational BIM vision, BIM goals, and specific BIM implementation plans. In addition, this criterion involves the allocation of financial resources as well as the establishment of BIM experts who support the implementation process. This result is underlined by the strong representation of leaders within this explorative BIM maturity study. One notable exception was seen with suppliers, in which many adopt a wait-and-see position since they are dealing with multiple clients, often with different needs.

Second, in terms of both the organizational structure criterion as well as the processes and procedures criterion, the results show that organizations have not given this significant attention. There is still a lot to gain from developing the formalization of tasks and responsibilities and of processes and procedures related to BIM. The findings indicate that these aspects have often lagged behind the rapid BIM development in other areas over recent years. A consequence is that BIM processes become highly dependent on individual competences, which could lead to divergent BIM performances between projects or between internal departments. Froese (2010) similarly argued that the full potential of BIM can only be achieved if changes are instituted in the organization structures, work practices, and skills of project members. Based on the research findings, it would seem that developments in the field of BIM typically run ahead of its institutionalization. In addition, there were several interviewees who felt that only limited changes to duties and responsibilities needed to be implemented. In their organizations, BIM is considered more as a supportive tool for other important organization activities. As such, the research shows that organizations have different expectations and perspectives regarding the use and consequences of BIM, and this presents a challenge to the implementation process (Davies and Harty 2013). Nevertheless, there is a general recognition that (inter)organizational business processes have to evolve and adapt to technological changes (Taylor and Bernstein 2009).

Further, many respondents emphasized the importance of our third criterion, people and culture, with respect to a successful

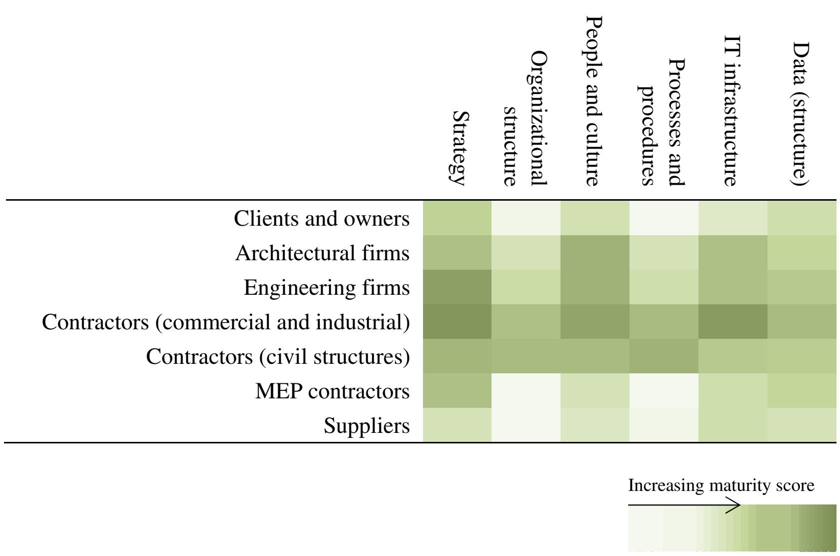

Fig. 9. BIM maturity scores of subsectors per BIM maturity criterion.

BIM implementation. Indeed, early adaptors identified aspects related to people and culture as the most challenging ones in the entire BIM implementation process. A majority of the respondents recognized that, if employees were not motivated to move on from existing practices, organization-wide adoption was difficult. This justifies the inclusion of people and culture as a main criterion in the BIM maturity model.

Our analysis of the people and culture maturity scores showed that these were generally relatively high. It appears that these aspects already receive considerable attention in the front-runner organizations in our sample, especially at the interviewed construction companies, architectural firms, and engineering companies. That is, they put effort into providing clear BIM information to employees, demonstrating the advantages of BIM for people's own work, and stressing the advantages that it may offer for the work of project partners or other disciplines. In addition, respondents emphasized that appropriate training and active guidance for employees, including the presentation of case studies, in the practical context are essential. The aforementioned aspects can help motivate employees to adapt to the BIM method of working, including its various roles and responsibilities (Gu and London 2010). It is particularly important that people become aware of the benefits of using BIM for their own work, their organization, and their projects.

When interpreting the outcomes of a BIM maturity analysis, one should not forget that an organization does not need to be at the highest maturity level on all the BIM criteria in order to work or cooperate in a BIM project. Depending on, for example, a comparative assessment of estimated costs and benefits or a limited clients' mandate for BIM, organizations can decide to set a target level below the maximum. Nevertheless, the maturity scores do provide valuable insights into those aspects that an organization should focus on to professionalize its use of BIM.

Evaluation of the BIM Maturity Tool

The content and suitability of the BIM maturity tool, comprising the maturity model and the interview format, were first appraised by submitting the model to all members of the supervisory group. After processing their feedback, the model was reviewed through some test interviews at organizations in various subsectors. The comments by the respondents were then processed in reaching the final maturity model and interview format for wider testing.

To ensure and evaluate the accuracy of the maturity model and interview format during the interview round, the interviewer also asked questions about any aspects that play a role in BIM that were missing. In this way, the sectoral analysis functioned both as a practical usage and as extensive testing of the maturity model and the interview format. In general, the respondents believed that all relevant aspects of BIM were covered in the interview. From this, it can be concluded that the contents of the maturity model and the accompanying interview questions sufficiently address the meaning of BIM. However, some respondents advocated a stronger anchoring of contractual aspects. Porwal and Hewage (2013) similarly emphasized the importance of contractual arrangements in improving productivity and project coordination. Moreover, Miettinen and Paavola (2014) concluded that the adoption of BIM in projects requires new contractual arrangements because of the changed collaboration between parties. One way to make contractual aspects more explicit in the maturity model would be to add this aspect in the context of the project structure for BIM. Here one could address the formalization of BIM-related processes between organizations, thereby complementing the within organization arrangements already covered by the organizational structure criterion.

In addition, from the overall exercise, the research team came to the conclusion that extra attention should be paid to the trust-related aspects of openness and transparency between parties in respect to BIM during any further development of the BIM maturity model. The temporary nature of collaboration between organizations in construction projects hampers the process of building trust because trust is influenced positively by past experiences and future expectations of collaborating partners (Laan et al. 2012). The research team further believes that BIM can be a driver of change and improvements in processes. This effect on process change could be included in the further development of the BIM maturity model within the processes and procedures criterion.

Once these enhancements have been incorporated in the assessment tool, the next step in the BIM maturity research will be to focus on further implementation of the BIM maturity model and in particular to develop a survey tool as a data collection method. Using such a tool will enable a more generic picture of BIM maturity to be obtained from a wider sample, enabling the BIM maturity model to be further tested and refined once again.

In addition, tools such as the Virtual Design & Construction (VDC) scorecard (Kam et al. 2014) could be evaluated to extend the use of the BIM maturity model to the project level. Investigating the potential of the developed BIM maturity model on the project level is particularly relevant because collaborative aspects are expected to be particularly beneficial within a project context.

Conclusions

The objective of this research was to provide insights into BIM developments within the various subsectors of the Dutch construction industry by developing and using a BIM maturity model and accompanying data collection methods. Unlike existing BIM maturity tools, the development of the presented BIM maturity model focused on both technical and organizational aspects of BIM, incorporating collaborative aspects between parties. In addition, the developed model aimed to support clear and mutually comparable BIM maturity assessments for making comparisons across the various disciplines within the construction industry. Based on the strengths of several existing maturity models, the structure and components of the proposed model were described. The model broke BIM down into 6 main criteria and 16 subcriteria, whose maturity levels were to be classified on a scale from 0 to 5. Once the basic BIM maturity model was established, it was translated into an interview format that was used to collect data from 53 firms in the Dutch construction industry. This implementation of the model also served to validate the BIM maturity tool. The in-depth interviews provided insights into differences and similarities among the subsectors. The main findings from the sectoral analysis can be summarized by three core elements:

- First, the evaluated leading companies demonstrated strong strategic support for BIM by setting goals, making BIM plans, and providing sufficient resources for BIM implementation.
- Second, the maturity scores for the formalization of BIM-related processes, tasks, and responsibilities were lower than for other criteria despite their relevance being acknowledged by the respondents.
- Third, respondents emphasized the importance of people and culture in the BIM implementation process. Influencing personal motivation and improving BIM-related competences were identified as essential means for supporting change of people and culture.

The BIM maturity assessment identified differences between subsectors that could be utilized by subsector-specific associations

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to develop industry-wide policies and diminish the gaps in BIM maturity and perspectives among the industry's subsectors.

The responses to the invitations to be part of our interviews indicated that the extent to which organizations were engaged in BIM implementation influenced their willingness to take part. Organizations that believed they were lagging behind in implementation often indicated that participation in the research was not relevant for them. Conversely, leading companies often saw benefits in gaining a sense of their own BIM progress in relation to developments in their subsector and in the construction industry in general. Further, these organizations have already encountered several barriers that have hindered implementation and often found ways to overcome them. As such, the interviews with those leading the way were especially valuable, not only providing more extensive information on the BIM maturity criteria, but also on presenting attention points regarding BIM implementation. Nevertheless, when interpreting the results, one should be aware that the sample used does not allow generalization to the entire construction industry.

Based on this study, the following directions for further research are proposed:

- First, it would be useful to further explore the applicability of the developed BIM maturity model by incorporating the aspects from the evaluation in its design and, subsequently, by conducting more extensive sectoral analyses. A related research topic would be to analyze to what extent the findings here on BIM maturity, at primarily leading companies in this field, are representative of the Dutch or European construction industries as a whole. Further, is the maturity model developed here also valuable for organizations that are lagging behind?
- Second, it would be relevant to analyze whether an increase in BIM maturity corresponds with an increase in BIM performance on the firm and project level. A related issue would be to explore how the BIM maturity model can be applied to support effective collaboration on the project level.

Based on this study, the following recommendations can be made for practice:

- First, focusing on organizations, there is a need for BIM education and training. According to many of the interviewed BIM managers, learning could be accelerated by linking more general education and training with specific BIM-related support in projects (on-the-job training).
- Second, sectoral associations need to further clarify BIM definitions of subsectors to enable mutual understanding of one another's BIM uses. Linking these perspectives would help close the gap between subsectors and thereby foster multidisciplinary BIM use in projects.
- Third, although many standards are already used by the various disciplines, the maturity and fragmentation of standards is regarded as a point needing attention. A sectoral priority for encouraging collaboration between subsectors is therefore the further development and adoption of standards that transcend subsectors.
- The final recommendation to organizations in the construction industry is to formally standardize tasks, responsibilities, processes, and procedures with regard to adopted BIM methods. Doing so will encourage the reliability and consistency of BIM processes and accelerate organizational learning.

Data Availability Statement

The data generated and analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

References

Adriaanse, A. M. 2007. "The use of interorganisational ICT in construction projects: A critical perspective dissertation." Ph.D. thesis, Univ. of Twente.

Adriaanse, A. M., J. T. Voordijk, and G. Dewulf. 2010. "Adoption and use of interorganizational ICT in a construction project." *J. Constr. Eng. Manage.* 136 (9): 1003–1014. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000201.

Alshawi, M. 2007. *Rethinking IT in construction and engineering: Organizational readiness*. London, UK: Taylor & Francis.

Bew, M., J. Underwood, J. Wix, and G. Storer. 2008. "Going BIM in a commercial world." In *Proc., European Conf. on Product and Process Modeling (ECPPM)*. Sophia Antipolis, France: Taylor & Francis.

Bryde, D., M. Broquetas, and J. M. Volm. 2013. "The project benefits of building information modelling." *Int. J. Project Manage.* 31 (7): 971–980. https://doi.org/10.1016/j.ijproman.2012.12.001.

Computer Integrated Construction Research Program. 2013. *BIM planning guide for facility owners*. State College, PA: Pennsylvania State Univ.

Davies, R., and C. Harty. 2013. "Measurement and exploration of individual beliefs about the consequences of building information modelling use." *Constr. Manage. Econ.* 31 (11): 1110–1127. https://doi.org/10.1080/01446193.2013.848994.

Eadie, R., M. Browne, H. Odeyinka, C. McKeown, and S. McNiff. 2013. "BIM implementation throughout the UK construction project lifecycle: An analysis." *Autom. Constr.* 36 (Dec): 145–151. https://doi.org/10.1016/j.autcon.2013.09.001.

Eastman, C., P. Teicholz, R. Sacks, and K. Liston. 2011. *BIM handbook: A guide to building information modelling for owners, managers, architects, engineers, contractors and fabricators*. Hoboken, NJ: Wiley.

Froese, T. M. 2010. "The impact of emerging information technology on project management for construction." *Autom. Constr.* 19 (5): 531–538. https://doi.org/10.1016/j.autcon.2009.11.004.

Gu, N., and K. London. 2010. "Understanding and facilitating BIM adoption in the AEC industry." *Autom. Constr.* 19 (8): 988–999. https://doi.org/10.1016/j.autcon.2010.09.002.

Indiana University. 2009. *IU BIM proficiency matrix*. Indiana Univ. Architect's Office.

Kam, C., D. Senaratna, B. McKinney, Y. Xiao, and M. Song. 2014. *The VDC scorecard: Formulation and validation*. Stanford, CA: Stanford Univ.

Laan, A., J. T. Voordijk, N. Noorderhaven, and G. Dewulf. 2012. "Levels of interorganizational trust in construction projects: Empirical evidence." *J. Constr. Eng. Manage.* 138 (7): 821–831. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000495.

Liang, C., L. Weishung, S. Rowlinson, and X. Zhang. 2016. "Development of a multifunctional BIM maturity model." *J. Constr. Eng. Manage.* 142 (11): 06016003. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001186.

Lockamy, A., and K. McCormack. 2004. "The development of a supply chain management process maturity model using the concepts of business process orientation." *Supply Chain Manage. Int. J.* 9 (4): 272–278. https://doi.org/10.1108/13598540410550019.

Miettinen, R., and S. Paavola. 2014. "Beyond the BIM utopia: Approaches to the development and implementation of building information modeling." *Autom. Constr.* 43 (Jul): 84–91. https://doi.org/10.1016/j.autcon.2014.03.009.

National Institute of Building Sciences. 2012. *National BIM standard: United States version 2, buildingSMART alliance*. Washington, DC: National Institute of Building Sciences.

Porwal, A., and K. N. Hewage. 2013. "Building Information Modeling (BIM) partnering framework for public construction projects." *Autom. Constr.* 31 (May): 204–214. https://doi.org/10.1016/j.autcon.2012.12.004.

Sarshar, M., M. Finnemore, R. Haigh, and J. Goulding. 1999. "SPICE: Is a capability maturity model applicable in the construction industry." *Durability Build. Mater. Compon.* 8 (1): 2836–2843.

Silver, M. S., M. L. Markus, and C. M. Beath. 1995. "The information technology interaction model: A foundation for the MBA core course." *MIS Q.* 19 (3): 361–390. https://doi.org/10.2307/249600.

Siriwardena, M. L., M. Kagioglou, K. S. Jeong, R. Haigh, and D. Amaratunga. 2005. "SPICE 3: Facilitating organisational process improvement through good practice sharing." In *Proc., 2nd Int. SCRI Symp*. Salford, UK.

Software Engineering Institute. 2010. *CMMi for development*. Pittsburgh, PA: Carnegie Mellon Univ.

Succar, B. 2009. "Building information modelling framework: A research and delivery foundation for industry stakeholders." *Autom. Constr.* 18 (3): 357–375. https://doi.org/10.1016/j.autcon.2008.10.003.

Taylor, J. E., and P. G. Bernstein. 2009. "Paradigm trajectories of building information modeling practice in project networks." *J. Manage. Eng.* 25 (2): 69–76. https://doi.org/10.1061/(ASCE)0742-597X(2009)25:2(69).

Vaidyanathan, K., and G. Howell. 2007. *Construction supply chain maturity model: Conceptual framework*. East Lansing, MI: International Group for Lean Construction.

van Berlo, L., T. Dijkmans, H. Hendriks, D. Spekkink, and W. Pel. 2012. "BIM quickscan: Benchmark of BIM performance in the Netherlands." In *Proc., CIB W78 2012: 29th Int. Conf.* Delft, Netherlands: International Council for Research and Innovation in Building and Construction.

Verschuren, P., and H. Doorewaard. 2007. *Het ontwerpen van een onderzoek*. The Hague, Netherlands: Uitgeverij Lemma.