Construction Innovation: Information, Process, Management

On the potential of integrating Building Information Modelling (BIM) for the Additive Manufacturing (AM) of concrete structures

Journal:	*Construction Innovation: Information, Process, Management*
Manuscript ID	CI-07-2019-0057.R3
Manuscript Type:	Research Article
Keywords:	BIM, Additive Manufacturing, 3D printing, Concrete, Digital transformation, Autonomous construction

Title: On the potential of integrating Building Information Modelling (BIM) for the Additive Manufacturing (AM) of concrete structures

Abstract

Purpose: Additive Manufacturing (AM) and Building Information Modelling (BIM) are emerging trends for which it has been claimed that both increase both efficiency and productivity in the construction industry. The aim of this study is to synthesise and aggregate the literature addressing BIM integration in the AM of concrete structures and to exploit the joint value creation potential.

Design/methodology/approach: This study firstly applies a mixed-review method in order to achieve mutual corroboration and interdependency between quantitative and qualitative research approaches. Bibliometric mapping is applied to identify, map and synthesise the relevant literature. Scoping review is used to examine the extent, gap, range and nature of the research activity. Afterward, a cross-situational analysis, *TOWS² Matrix*, is proposed and applied to exploit the joint value creation potential of different aspects of AM and BIM.

Findings: The study reveals a substantial interest in this field. However, progress in terms of integration is slow compared to the rapid development in interest in the two trends individually. The literature discusses or conceptualises such integration at building-scale, while prototyping or PoC processes are only rarely employed. The study identified 12 joint value creation potentials through the integration of BIM in AM for concrete structures, which can create value by enabling more optimised designs, automated construction processes, and data analytics that can apply throughout the building life-cycle process.

Originality/value: The advancements of BIM integration in the AM of concrete structures are analysed and joint value creation potentials are proposed. The study proposes a cross-situation analysis that can be applied to structure joint value creation potentials from the multi-dimensional integration of different factors and topics, especially for emerging technologies.

1 Introduction

Additive Manufacturing (AM) and Building Information Modelling (BIM) are emerging trends within the construction industry. It has been argued that both have transformed the industry by increasing efficiency and productivity. According to the US National Institute of Building Sciences (NIBS, 2019), BIM *is "a digital representation of physical and functional characteristics of a facility"*. According to the American Society for Testing and Materials (Technologies and Terminology, 2012), AM is defined as "*the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies*".

The additive manufacturing, or more popularly "3D printing", of concrete structures/constructions (CC) is regarded as a disruptive technology, superior to conventional construction methods (Labonnote et al., 2016, Buswell et al., 2018). The benefits of AM in the construction industry include freeform choice at no extra cost, increased sustainability, greater reliability and wider reach. Despite the fact that several large-scale applications have successfully been adopted in the construction industry, AM is still regarded as being at an early stage of adoption. Most research and development in the field of AM for concrete structures are focused on robot development, hardware improvements, materials performance research and to a much lesser extent, on software development; despite the fact that geometrical 3D modelling is a requirement for the construction process.

BIM's multi-dimensional capacity and functionality extend the dimensional applications of conventional 3D digital modelling by offering scheduling, cost estimation, sustainability, facility management application and up to and including safety (Bryde et al., 2013). BIM offers seamless workflow integration and management of the entire life-cycle process, including the sub-processes of design, analysis, fabrication, construction, operation, maintenance, renovation and end-of-life. Many building projects are currently implementing a BIM software platform (Li et al., 2019). However, there are clear indications that this level of maturity and interoperability capabilities can be built on to extend beyond conventional construction applications. One such application may be additive manufacturing of constructions.

The current respective employment of these two new technologies is driven by different factors associated with different stages of a building's life-cycle process. On the one hand, they share similar requirements that may facilitate easier integration. On the other, however, one may display distinct characteristics that may enhance or complement the benefits of the other. A higher level of autonomous building construction may be achieved by employing a form of AM of concrete structures in which the robot's activity, scheduling and assembly sequence are coordinated using BIMs. In the light of this, the integration of these two technologies has been attracting the attention of the research community in recent years despite the fact that neither has achieved the maturity required to be considered as fully implemented or integrated into industry practice.

The aim of this study is to synthesise and aggregate the literature addressing BIM integration in the AM of concrete structures, and to exploit the joint value creation potential of their multi-dimensional integration. A mixed-review method and a proposed cross-situational analysis have been carried out to address this aim by means of the following objectives:

- the identification, mapping and synthesis of relevant literature (Section 3.1);
- an investigation of the extent, range and nature of research activity, including research gaps (Section 3.2); and
- the exploitation of the joint value creation potential inherent in implementing BIM in the additive manufacturing of concrete structures (Section 4).

2 Methodology

2.1 Overall methodology

Research into the integration of BIM in AM is relatively new fragmented. For this reason, this study firstly applies a mixed-review method in order to achieve mutual corroboration and interdependency between quantitative and qualitative research approaches. Afterwards, a cross situational analysis is proposed and developed as a method to exploit the joint value creation potential of the multi-dimensional integration of different aspects of AM and BIM. A general schematic overview of methods as they relate to the objectives is presented in Figure 1. Detailed information is provided in subsequent subsections in this chapter. Three main research methods have been employed:

1) a mixed-review method, by conducing
    a. bibliometric mapping
    b. a scoping review
2) a TOWS[2] analysis

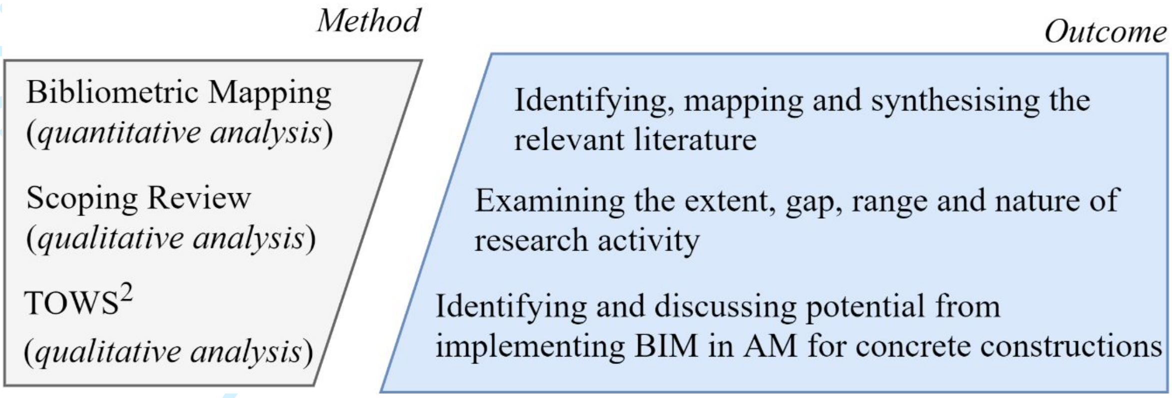

Figure 1. General schematic overview of the methodology

2.2 Mixed-review method

2.2.1 Bibliometric mapping

Bibliometric mapping, or science mapping, attempts to identify and represent the intellectual connection within a dynamically changing system of scientific knowledge (Small, 1997). It is a statistical analysis approach involving the following steps (Cobo et al., 2011): data preprossessing, a normalisation process, statistical analysis, and visualisation. This paper applies bibliometric mapping to identify and map the patterns and trends of the integration of two topics in comparison to the advancements of their specific ones, and to understand the focus of the research based on cluster analysis. Visualisation of co-authorship, citation, bibliographic coupling and co-citation mapping falls out of the scope of this study. VOSviewer (van Eck and Waltman, 2009) is a free software tool used in this study to construct and visualise bibliometric mapping. The VOS mapping technique builds a two-dimensional map in which the distance between any given pair of elements reflects their similarity. VOSviewer is used to perform community detection using the VOS clustering technique, which is related to modularity-based clustering (Cobo et al., 2011). In order to stem words, all keywords obtained from different literature sources during the data preprocessing stage are edited (for example, the terms *BIM*; *Building information model*; *Building information modelling* and *Building information modeling* should contain the same meaning). The selected keywords and Boolean operators are presented in the next subsection. As part of this search, only literature published during the past decade in the electronic database Scopus has been investigated.

2.2.2 Scoping review

The scoping literature review carried out in this study is based on an established research methodology (Booth et al., 2011, Arksey and O'Malley, 2005) that ensures a comprehensive search process and systematic review of the relevant literature. The methodology originates from the field of health and social sciences, but its principles are applicable to other fields of study. It offers a tool capable of providing a transparent and reproducible research synthesis that offers greater clarity, internal validity and audibility (Booth et al., 2011). The aim of a scoping review is to provide an in-depth coverage of available literature with the aims of (a) examining the extent, range and nature of research activity, (b) determining the value of undertaking a full systematic review, (c) summarising and disseminating research findings and (d) identifying research gaps in the existing literature (Arksey and O'Malley, 2005).

The first step in the review process is to define the scope of published research that directs focus on the research question (Booth et al., 2011, Arksey and O'Malley, 2005). In the present study, the research question opts to identify how and to what extent a BIM platform can be implemented in the additive manufacturing of concrete structures. The CIMO framework (Petticrew and Roberts, 2008) is used to define the key concepts of the research process (Table 1). The research question is identified as follows:

"How can the additive manufacturing (**I**) of concrete structures (**C**) and BIM platforms (**M**) benefit from their integration (**O**)?"

Table 1.The CIMO framework

Context	concrete structures/ concrete buildings/ concrete components/ concrete elements
Intervention	additive manufacturing/ 3D printing
Mechanisms	implementation of BIM platform/ integration of two digital technologies to enhance productivity
Outcomes	more digitalised platforms or autonomous processes for the additive manufacturing of concrete structures

Table 2. Keywords and Boolean operators

Who? *(concrete structures)*		**What?** *(AM)*		**How?** *(BIM)*
Intervention		**Context**		**Outcomes/Mechanisms**
concrete	and	"3D-printing"	and	BIM
building*		"additive manufacturing"		"Building Information Model*"
construction*		"4D-printing"		"Building Information Management"
cement*		"contour crafting"		
structure*				

The keywords presented in Table 2 were identified based on the titles, abstracts and keywords obtained from the literature following a preliminary screening (first step) using the electronic databases Scopus and Google Scholar. Three electronic databases containing peer-reviewed literature were used for the final screening (second step). Scopus, Web of Science and Engineering Village are all relevant sources of information in this research field. The search scheme and exclusion criteria are shown in Figure 2 and Table 3. The keywords, operators and nesting combinations are presented in Table 2. The keywords were applied at *title, abstract, keywords* and *topic* levels. The final search was performed in November 2018. All years of publication were included in the search process.

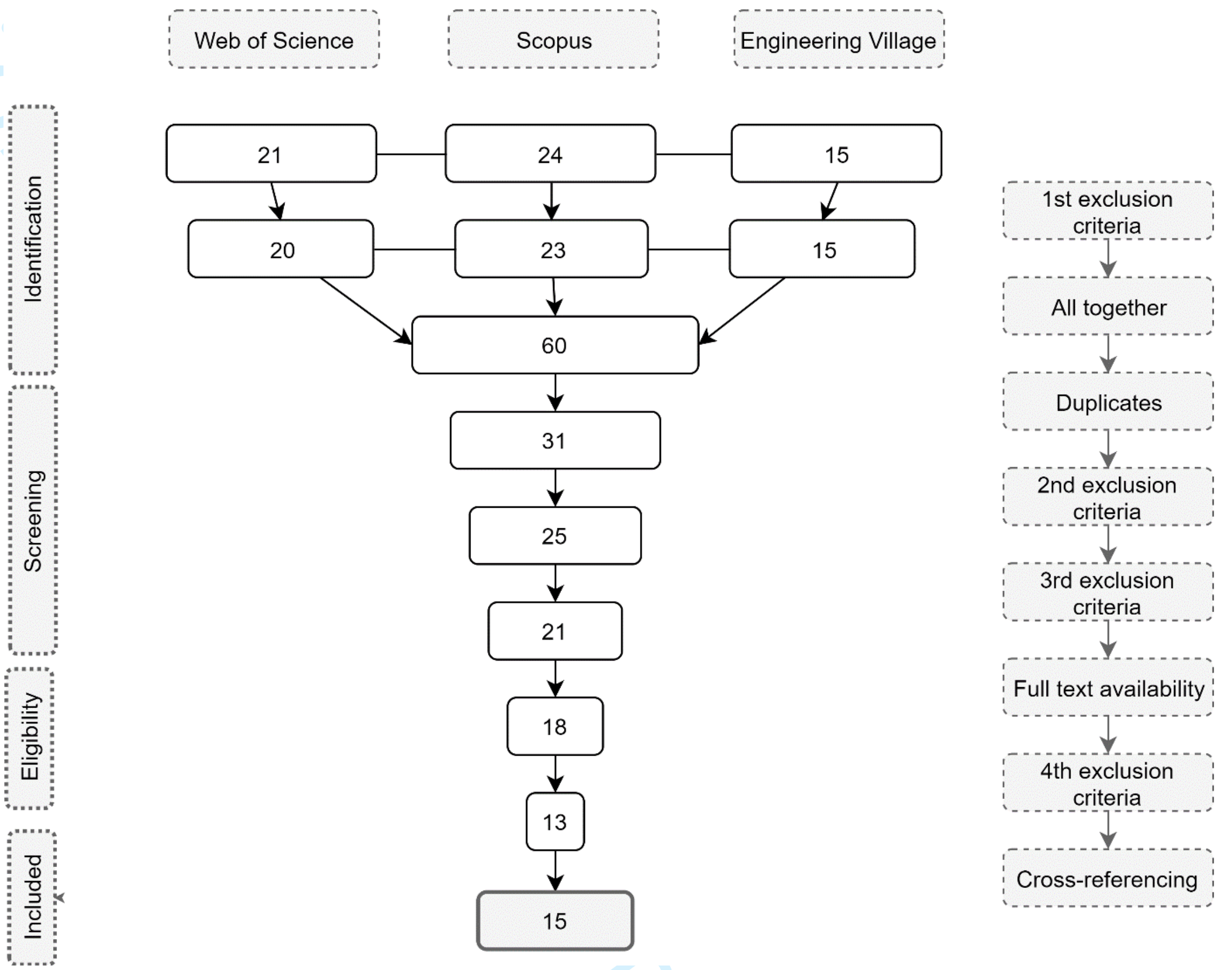

Figure 2. PRISMA framework (Moher et al., 2009) showing the literature screening process

Literature screening based on a full-content and cross-referencing methodology, combined with author searching, was used to check for additional sources. The final number of publications selected was 15 (Sakin and Kiroglu, 2017, Tay et al., 2017, Ding et al., 2014, Tan, 2018, van der Zee et al., 2014, Kim et al., 2015, Subrin et al., 2018, Tibaut et al., 2016, Kouch et al., 2018, Davtalab et al., 2018, Salet and Wolfs, 2016, Lu et al., 2016, Correa, 2016, Perkins and Skitmore, 2015, Teizer et al., 2018). Subsequently, a data extraction process (Booth et al., 2011) was developed to retrieve and code relevant variables and elements in order to enable comparisons and identify patterns, themes or trends. Figure 3 shows the main pathways that helped to chart the literature review results described in the following sections.

Table 3. Exclusion criteria

Exclusion	*1st exclusion criterion*	*2nd exclusion criterion*	*3rd exclusion criterion*	*4th exclusion criterion*
Reason for exclusion	Qualitative, based on literature type	Scientific, based on keywords and titles	Scientific, based on abstracts	Scientific, based on article and quality assessment
What is excluded	Literature other than Articles; Reviews; Proceeding Papers; Book chapters; in English	Additive manufacturing involving mini-scale prototypes of buildings, such as used in architectural contexts. Additive manufacturing of products not related to the construction industry. No mention of a relationship between BIM and AM throughout the publication.		

Figure 3. Schematic overview of literature extraction pathways

2.3 The *TOWS^2 Matrix* – a cross-situational analysis for exploiting joint value creation potentials

2.3.1 TOWS^2 Matrix: the method

Attempts to improve corporate strategy development processes have fostered a number of different approaches, among which one of the most popular is the SWOT analysis (Jackson et al., 2003). The SWOT analysis provides a tool for the identification and analysis of internal and external factors that impact positively or negatively on an enterprise's ability and capacity to create value. It identifies factors within four categories: the strengths (S), weaknesses (W), opportunities (O) and threats (T) associated with business competition or project planning. It continues to remain a popular strategy today among research scientists, and in particular those considering the implementation of new technologies, for example BIM (Isikdag and Zlatanova, 2009, Joblot et al., 2019) or AM (Sobotka and Pacewicz, 2016, Smelov et al., 2014). Despite its popularity, a SWOT analysis only maps the key factors that impact on the topic of interest and does not reveal the relationships between these factors. What is often overlooked is that combining these factors may require strategic choices, and this is the reason why the TOWS Matrix tool has been proposed (Weihrich, 1982) as a means of systemising these choices. The TOWS Matrix defines four distinct strategies for a given topic of study, which in practice may overlap depending on the interaction of any two factors from the four categories identified in a SWOT analysis (Weihrich, 1982). However, the scope of each aforementioned analysis fails to accommodate the use of multi-dimensional capabilities generated from the integration of more than two factors or categories. This becomes even more evident in situations where an analysis seeks to exploit the integration of two topics, especially where these topics are regarded as "non-mature" (yet to be established *per se*), and thus characterised by uncertainties due to a lack of the information required to carry out any of the analyses required for their integration.

In the light of the above, this study introduces the *TOWS^2 Matrix* approach, which represents a further modification of the SWOT tool and the TOWS Matrix, with the aim of structuring joint value creation potentials from the multi-dimensional integration of different factors and topics. Potentials are generated by exploiting the cross-situational opportunities (O) revealed by matching the strengths (S) with the weaknesses (W) and threats (T) identified for joint or individual topics. A given situation can be analysed in three different ways: (a) by identifying important problems, (b) by determining purposes and objectives and (c) by focusing on opportunities (Weihrich, 1982). Our method aims to identify the potentials that are driven by the integration of distinct topics, and this study will thus focus on alternative (c). A schematic presentation of the *TOWS^2 Matrix* is given in Figure 4. The process is based on the following steps:

1- Performance of a SWOT analysis and identification of individual factors corresponding to each of the four categories (strengths, weaknesses, opportunities and threats) for Topics 1 and 2. To classify each variable under one of the following fields: technology; business; legal; environmental; and societal.

2- Construction of a *TOWS² Matrix* by identifying the relevant combinations of factors from Topics 1 and 2 that address the focus selected in step 1, and evaluate potentials from each selected combination. This will involve either the enhancement of existing effects that promote value creation capacity, or the triggering of new ones.

3- Selection of the combination that displays the greatest potential, the development of alternatives, and the making of strategic choices that address the identified enhanced or triggered effects.

2.3.2 TOWS² Matrix: execution of the method

The proposed TOWS² matrix is better adapted to a study of this type that focuses on exploiting the potentials derived by the integration of BIM and AM in relation to concrete structures. The process follows the followings steps:

<u>Step 1</u>: The SWOT analyses were developed based on an aggregation of the following:

- Previous relevant work carried out at the authors' research institute including interview-based reports,
- Personal communications with the ACE BIM Work Group within CEN/TC 442 – Building Information Modelling (Nore, 2018), and
- A collection of relevant publications (Isikdag and Zlatanova, 2009, Joblot et al., 2019, Labonnote et al., 2016, Uhm et al., 2017, Tang et al., 2019, Zheng et al., 2019, Abdal Noor and Yi, 2018, Mahamadu et al., 2019, Wang and Chong, 2015).

<u>Steps 2 and 3:</u> A workshop was held with BIM and AM experts from the authors' research institute with the aim of identifying potentials from the multi-dimensional integration of different factors associated with AM and BIM in relation to concrete structures. The results are discussed in section 4.

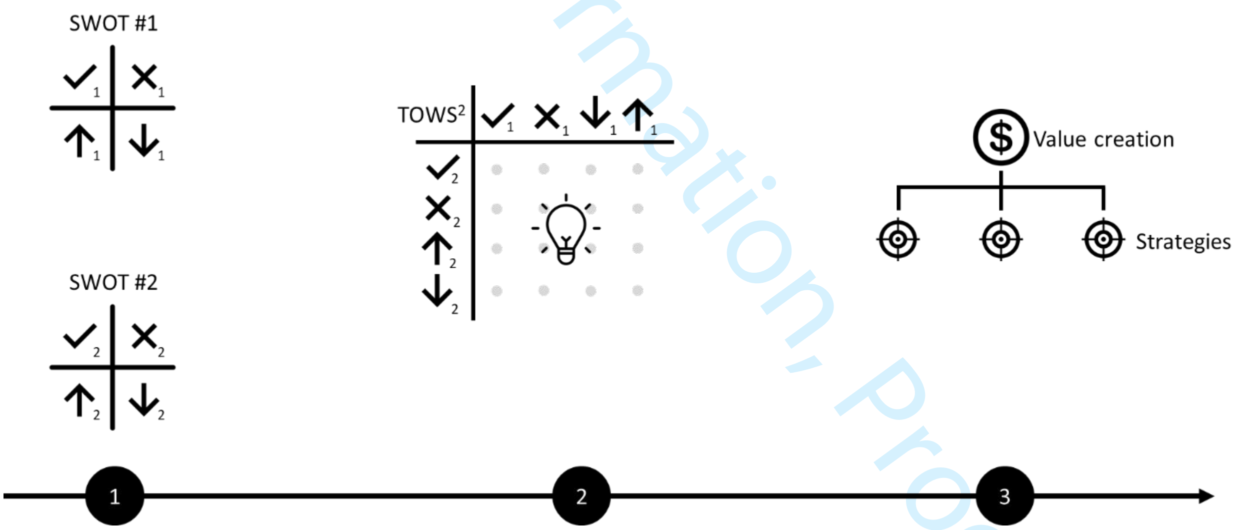

Figure 4. The TOWS² Matrix

3 Mixed-review Method: Results and Discussion

3.1 Bibliometric Analysis

3.1.1 Variation and distribution of literature

Figure 5 and Figure 6 respectively show the Venn diagram and the historical variation of the number of relevant studies based on different groups of literature. The groups are as follows:

- Group 1: *[BIM ∩ CC]*
- Group 2: *[AM ∩ CC]*
- Group 3: *[BIM ∩ AM]*

- Group 4: *[BIM ∩ CC ∩ AM]*

The results are summarised in the following:

- There exists a large body of literature for both BIM and AM. However, research involving the simultaneous application of both fields is very scarce. This finding agrees with the results of the McKinsey report (Agarwal et al., 2016), which analysed more than 2,400 technology companies and mapped emerging trends within the construction sector. The study revealed that while both BIM and AM are increasingly being implemented in the construction industry, it failed to identify any significant co-occurrence.
- During the last decade, research into both BIM and AM has developed rapidly, although their integration has only attracted interest among researchers in the last few years.
- The results from Group 3 and Group 4 are almost identical. This indicates that in these cases any discussion of the integration of BIM in AM has involved applications related to concrete structures. This simply reflects the fact that concrete is the most widely used building material in the world. Another possible reason is that the complexity involved in the construction of concrete structures is likely to benefit from the greater interoperability provided by BIM, which is less significant in connection with steel structures.

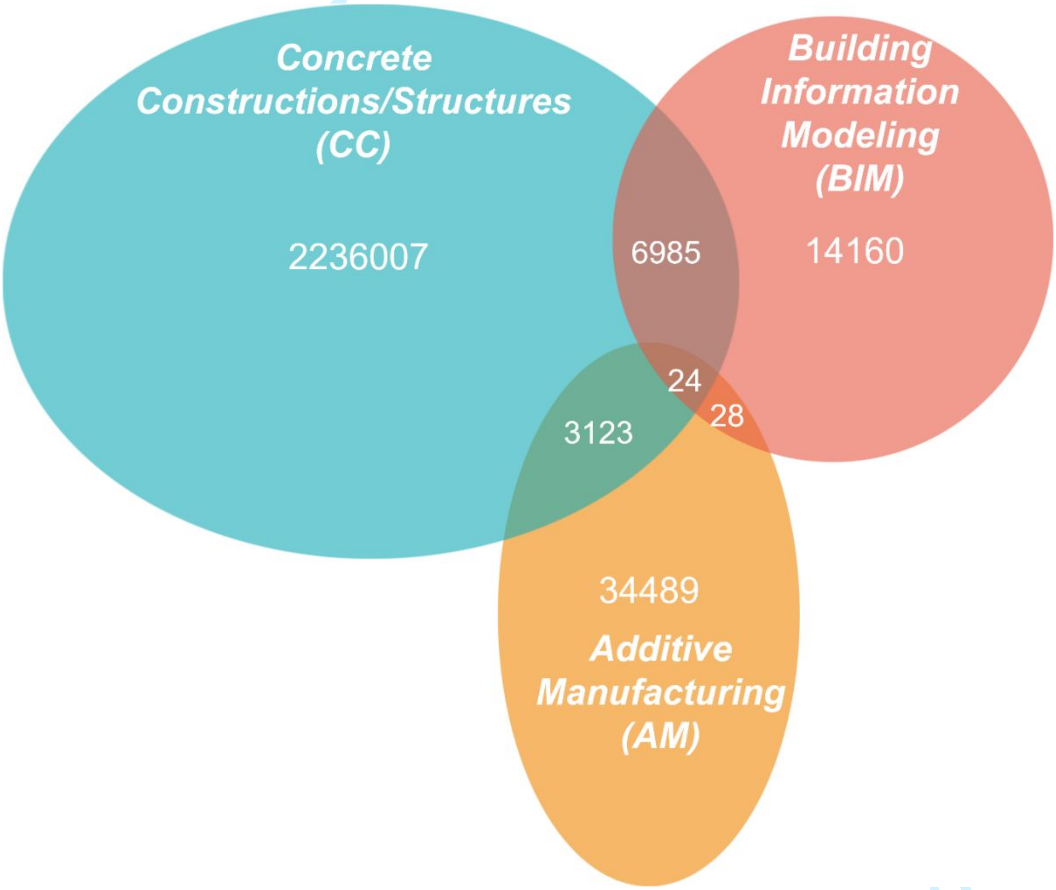

Figure 5 Venn diagram of the distribution of various literature sources based on different combinations of the keywords and Boolean operators set out in Table 2. This search has been performed only in Scopus database without any exclusion criteria.

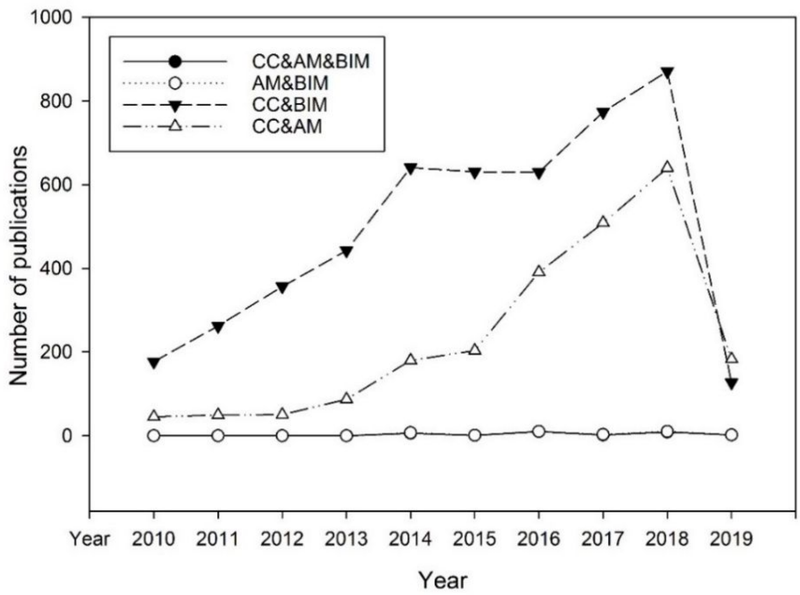

Figure 6 Historical variation of the number of published studies based on four different literature groupings. Group 1: [BIM ∩ CC]; Group 2: [AM ∩ CC]; Group 3: [BIM ∩ AM]; Group 4: [BIM ∩ CC ∩ AM].[1]

3.1.2 Co-occurrence analysis of author keywords

The results of the co-occurrence analyses of keywords for the large literature source groups *[BIM ∩ Concrete Structures]* and *[AM ∩ Concrete Structures]* carried out in the software VOSViewer, as presented in Section 3.1.1, show that none of the groups identify its counterpart (BIM or AM) as an important keyword. The analysis of the co-occurrence of author keywords is therefore employed in this study with the aim of describing patterns in the literature linked to the group *[BIM ∩ AM]*. Based on a cluster analysis, the following three main groups are identified:

Cluster 1 (red): Automation of construction by additive manufacturing

Cluster 2 (blue): Digital production and flow by means of additive manufacturing

Cluster 3 (yellow) and Cluster 4 (green): Digital design, interoperability and transformation of construction

The results (Figure 7) show that research here is focused primarily on the added value provided to the planning and construction process by means of automation. During the construction process the shift of the construction industry is observed in the automation of the process as enabled by robotics and additive manufacturing technology. The digital transformation of the planning process stems from the potential workflow integration and interoperability enabled by BIM platforms.

[1] Groups 3 and 4 are almost identical and thus follow the same plot.

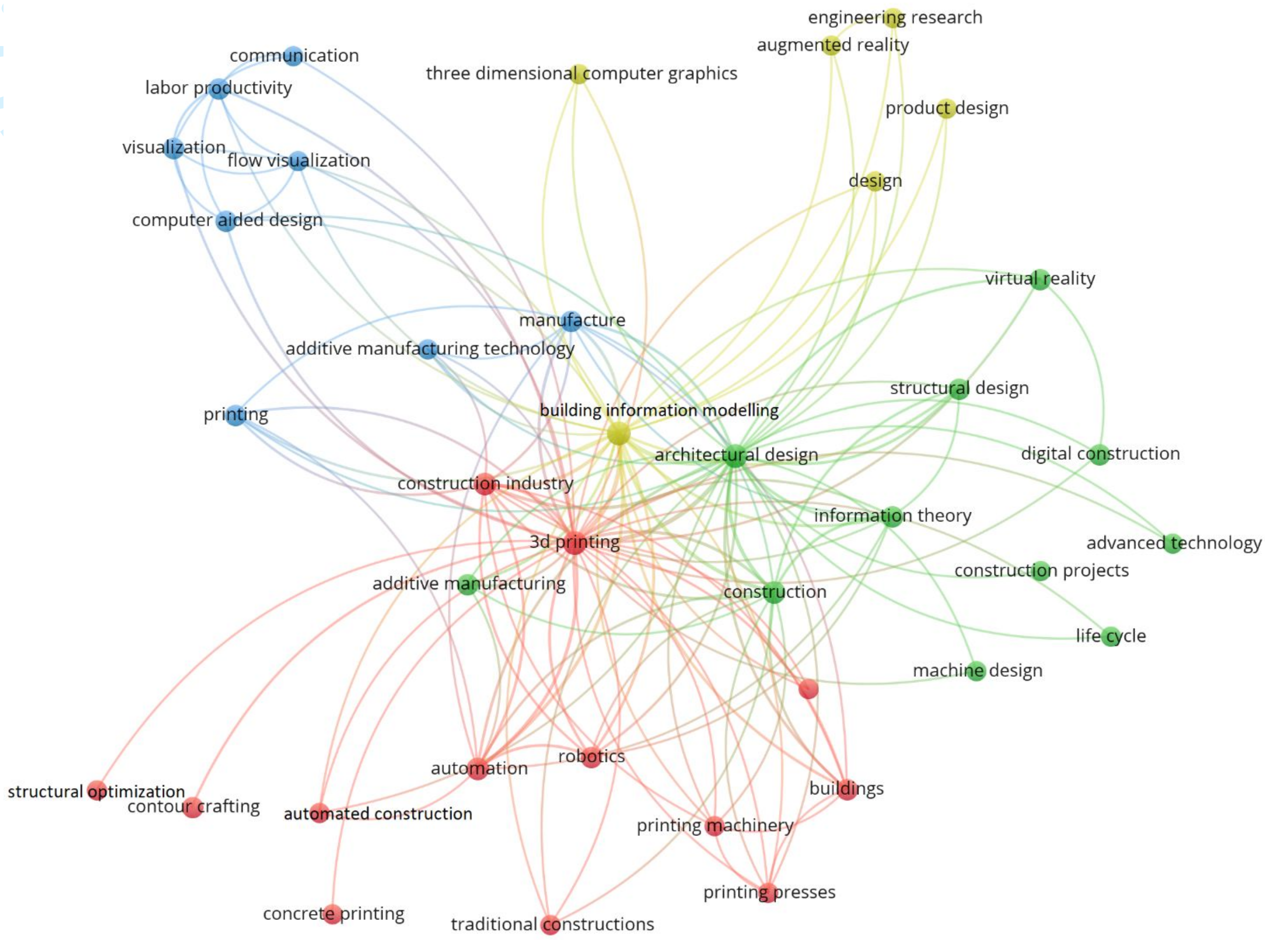

Figure 7. Co-occurrence analysis of authors' keywords. Different colours represent different clusters. The size of each bubble represents the weight of the keyword as determined by its total number of occurrences. The curved lines illustrate the connections between the keywords.

3.2 Results of the scoping review

3.2.1 General overview of the available literature

The literature sources identified by the foregoing process are presented in Table 4, where their specific characteristics are compared in relation to the selected variables. The results are:

- Almost all publications are derived from a variety of sources, including journal publications, book chapters/subsections or conference proceedings. No leading conference event or journal has been identified.
- The origins of the publications are almost uniformly spread across different institutes and countries. The great variety in origin of these sources indicates that this research field is in its early stages, with many authors anticipating its potential. According to the top ten list of countries working with BIM and AM, as presented in references (Zhao, 2017) and (Tay et al., 2017) respectively, when analysing the results of the institute origin from the scoping review (see Table 4), it is observed that 40% of the authors in countries primarily discussing BIM also discuss AM, while 60% of those that discuss AM also discuss BIM.
- Authors that have themselves carried out literature reviews both recognise and discuss the opportunities that arise from implementing BIM in the AM of on-site constructions. Opportunities for pre-fabrication, especially in connection with typology optimisation and form-finding, are also discussed.

277 - A few alternatives are proposed in connection with the implementation of BIM in AM, including the use of interfaces/software programs and the extension of IFC classes. In general, the authors agree on the process of implementing BIM in AM for concrete structures, which involves the translation of BIMs into STL files using IFC classes. Two software programs, BIMAC (Ding et al., 2014) and POCSAC (Davtalab et al., 2018), have been developed and conceptualised, but there exists only one real case study that has implemented BIM in additive manufacturing in a construction context (Subrin et al., 2018).

284

Table 4. General overview of the characteristics of the available literature discussing AM and BIM integration for concrete structures (listed chronologically)

Reference title	Year	Reference type	Source	Type	Institute origin	TRL - integration of BIM and AM	Scale of construction	Type of printer	Purpose/ construction	Software
Development of a BIM-based automated construction system (Ding et al., 2014)	2014	Conference proceedings	Creative Construction Conference	case study	China	PoC	Product	Contour crafting	on site	BIMAC
From rapid prototyping to automated manufacturing (van der Zee et al., 2014)	2014	Book chapter/ subsection	Fusion: Data Integration at Its Best	theoretical paper	Netherlands	Concept	Element		on site	
Implementing a digital model for smart space design: practical and pedagogic issues (Kim et al., 2015)	2015	Conference proceedings	International Conference on New Horizons in Education	theoretical paper	Republic of Korea	Concept	Building		on site	
Three-dimensional printing in the construction industry: A review (Perkins and Skitmore, 2015)	2016	Journal article	International Journal of Construction Management	literature review	Australia	Idea	Building		on site	
Robot-oriented design for production in the context of building information modeling (Correa, 2016)	2016	Conference proceedings	International Symposium on Automation and Robotics in Construction	case study	Brazil	PoC	Element	Prusa 3D printer	pre-fabrication	interface
A review of 3D printable construction materials and applications (Lu et al., 2016)	2016	Conference proceedings	International Conference on Progress in Additive Manufacturing	literature review	Singapore	Idea	Building		on site	
Potentials and challenges in 3D concrete printing (Salet and Wolfs, 2016)	2016	Conference proceedings	International Conference on Progress in Additive Manufacturing	mixed-methods (review and theoretical)	Netherlands	Idea	Building	Contour crafting	on site	
Integrated Design in Case of Digital Fabricated Buildings (Tibaut et al., 2016)	2016	Conference proceedings	International Conference on Sustainability in Energy and Buildings	conceptual paper	Slovenia	Concept	Building		on site	
3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM (Sakin and Kiroglu, 2017)	2017	Conference proceedings	International Conference on Sustainability in Energy and Buildings	theoretical paper	Turkey	Concept	Building		on site	
3D printing trends in building and construction industry: a review (Tay et al., 2017)	2017	Journal article	Virtual and Physical Prototyping	literature review	Singapore	Idea	Building			
Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting (Davtalab et al., 2018)	2018	Journal article	Automation in Construction	case study	USA	PoC	Element	Contour crafting	on site	POCSAC
Key factors of an initial BIM implementation framework for small and medium-sized enterprises (SMEs) (Kouch et al., 2018)	2018	Conference proceedings	International Symposium on Automation and Robotics in Construction	mixed-methods (review and theoretical)	Finland	Idea	Building			
Improvement of the mobile robot location dedicated for habitable house construction by 3D printing (Subrin et al., 2018)	2018	Conference proceedings	International Federation of Automatic Control	case study	France	Prototype	Building	FAM	on site	
BIM for 3D printing in construction (Teizer et al., 2018)	2018	Book chapter/ subsection	Springer, Nature (2018)	case study	Germany	PoC	Building	AG VX4000	pre-fabrication	

3.2.2 *Historical development and trends*

A historical illustration of identified publications that discuss the implementation of BIM in AM in concrete structures is shown in graphical form in Figure 8. The results show that:

- the discussion on the implementation of BIM in AM has only been ongoing in recent years.
- while the distribution of publications concerning the application of AM or BIM platforms in the construction industry exhibits an increasing, log-normal distribution over the years (Antwi-Afari et al., 2018, Zhao, 2017, Labonnote et al., 2016), discussion on their integration shows a somewhat irregular trend.
- the publication types comprise mostly conference proceedings (10), followed by journal articles (3) and book chapters/subsections (2). Journal publications are distributed uniformly over the past three years.

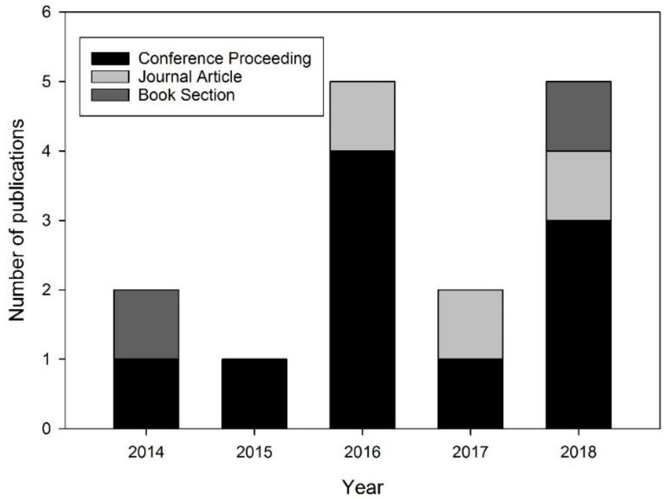

Figure 8. Historical development of selected references sorted according to literature source

3.2.3 *Extent of available literature and research gaps*

The selected literature has been categorised and structured based on two variables; Technology Readiness Level (TRL) and the scale of the structure in question (see Table 4). The TRL variable represents the extent of application of BIM in AM and is subdivided into the categories: idea, concept, Proof-of-Concept (PoC), prototype or application. The scale parameter indicates the scale/size of the AM structure and, based on the definitions set out in the ISO 6707-1:1989 standard (NIBS, 2004), is subdivided into the categories: product, element and building. The results are presented in Figure 9 and Figure 10 and constitute the following:

- Most of the literature sources discuss the application of BIM platform for a given building scale. It is true that the larger the scale of additive construction, the greater the need for interoperability and autonomous control, and consequently the greater the usefulness of application of a BIM platform.
- Three constellations of literature are observed based on trends linked to numbers of publications. In Figure 9, these are presented in the form of coloured quadrants defining different domains.
- The lower, right-hand, blue domain assembles the most popular fields of discussion. Many authors seem to have recognised the potential of implementing BIM in AM. However, a low TRL value shows that this is still very much a research field, with very few validated industrial applications.
- The upper, red, domain shows the implementation of BIM in AM, up to at least Proof-of-Concept level and regardless of the scale of the structure. This area constitutes a research gap, as reflected in the paucity of currently available literature. Research appears not to focus on any particular structural scale, which somewhat goes against the popular science trend to advertise full-scale 3D-printed constructions, such as the first 3D-printed office hotel (COBOD), the first 3D-printed bridge

(MX3D), the first 3D-printed office building (Foundation) and the first 3D-printed social housing building fully approved by the European authorities (Batiprint3d).

- The lower left-hand green domain, which focuses on literature related to the implementation of BIM at product scale, is clearly an under-researched topic. This may probably be due to the fact that the advantages of employing BIM at product scale are not considered as efficient as at building scale.
- The literature addressing the implementation of PoCs or prototypes is very distinctive and in some cases not detailed, whereas that discussing or conceptualising the integration of BIM and AM is widely dispersed and somewhat similar. The current status of the literature as a whole is considered insufficient as a basis for carrying out a more in-depth systematic review.

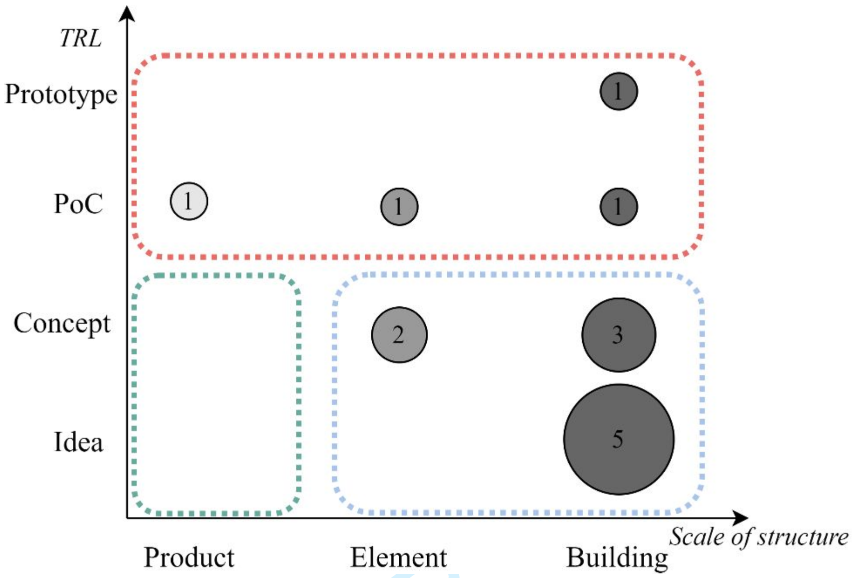

Figure 9. Categorisation of literature based on the scale of structure (x-axis) and Technology Readiness Level (TRL) (y-axis). The size of the circles and the number enclosed therein indicate the number of publications corresponding to the specific scale of building and TRL parameters.

Figure 10. Historical development of selected literature sorted according to TRL and scale of structure.

4 Benefits of implementing BIM in additive construction: a qualitative analysis: *TOWS*[2] cross-situational analysis

4.1 SWOT analyses

The results of the SWOT analyses for AM and BIM for concrete structure are respectively presented in tabular format in Table 5 and Table 6. They are further interrelated to identify exploit the opportunities from matching the strengths with the weaknesses and threats of the joint or individual technologies. The results are presented and discussed in the next section. The scope of this study focused on concrete structures due their steadily increasing applications in building industry; however, the research may be further extended and it is hoped that similar studies extending the present scope to non-concrete structures and possibly to the transportation infrastructure sector will identify similar substantial societal and economic benefits.

Table 5. SWOT analysis: AM for concrete structures[2]

	Internal Strengths (S)		**Internal Weaknesses (W)**
1	*(b)* complexity at no extra cost	1	*(t)* prolonged production time
2	*(t)* reliability (robotic precision)	2	*(t)* anisotropic resulting structural material properties
3	*(b)* uninterrupted job completion (robotics)	3	*(t)* unknown durability
4	*(b)* less need for formwork	4	*(b&t)* rough finishing
5	*(b)* 'right first time' (no need for quality assurance)	5	*(t)* no formwork means limited scope for overhangs
		6	*(t)* reinforcement still manual mostly)
		7	*(e)* non-documented LCA for process
	External Opportunities (O)		**External Threats (T)**
1	*(b)* mass customisation business model	1	*(e)* concrete is not environmentally friendly
2	*(t)* development of new materials (*b*) circular economy	2	*(l)* lack of standardisation/certification of best practices
3	*(b)* integrated digital workflow from design to production	3	*(l)* lack of design principles
4	*(b)* optimisation: better performance, less materials	4	*(l)* lack of IPR guidelines
5	*(b)* design platform business model	5	*(l)* legal liability issues
6	*(b)* on-demand and on-location business model for world heritage restoration	6	*(l)* supply chain / decentralised manufacturing
7	*(s)* increased safety and wellbeing on site	7	*(s)* job / skills transition
8	*(b)* 'spare parts on demand' business model		
9	*(t)* compounded multipart as one product		
10	*(s)* more educational opportunities		

Table 6. SWOT analysis: BIM for concrete structures[3]

	Internal Strengths (S)		**Internal Weaknesses (W)**
1	*(t)* better planning process	1	*(b)* cost: software, training, scoping and implementation
2	*(t)* interoperability	2	*(t)* front-loaded process
3	*(t)* better visualisation	3	*(t)* difficult to observe and communicate design maturity levels and level of detail
4	*(b)* improved communication (client/designer)	4	*(s)* no collaboration culture across occupations
5	*(t)* data-rich gathering platform	5	*(t)* focus has been on building rather than information
6	*(l)* detailed documentation for different phases/ compliance checking	6	*(l)* governments need to take the lead
7	*(e)* controlled whole-life costs and environmental data	7	*(b&s)* conservative culture in the construction sector
8	*(t)* better O&M management	8	*(t)* it does not pay off for all types (small) of projects
9	*(t)* reduced risks and errors, clash detection	9	*(t)* in-house skills
10	*(t)* better design	10	*(t)* time consuming and complex to build
		11	*(t)* not suited to pre-design
		12	*(t)* non-intuitive user interface
	External Opportunities (O)		**External Threats (T)**
1	*(t)* interoperability with advanced techs (AI, VR, IoT)	1	*(b)* changes in process and ways of working
2	*(b)* networking	2	*(l)* liability and insurance risk

[2] *(b)* business, *(t)* technological, *(l)* legal, *(e)* environmental, *(s)* societal
[3] *(b)* business, *(t)* technological, *(l)* legal, *(e)* environmental, *(s)* societal

3	*(t)* BIM as a platform for retrieval of AEC data	3	*(l)* safety information (access, clouds, data protection)
4	*(l)* growing interest in standardisation	4	*(b)* reliance on supplier's/vendor's experts
5	*(e)* reduced energy use and construction waste	5	*(l)* new types of construction contracts will be needed
6	*(t)* automated assembly	6	*(s)* skills retention and salaries in the digital construction sector
7	*(s)* more educational opportunities		

4.2 Potential strategies obtained from the TOWS² cross-situational analysis

The results of the *TOWS² Matrix* analysis following the steps discussed in Section 2.3 are presented in Table 7 and summarised below in the form of twelve joint value creation potentials identified during this study. The second and third column show the individual factors from AM and BIM, whose joint combination was identified as a potential. The latter is derived as promoting value creation capacity or triggering new ones. The potentials are categorised based on how they correspond to different stages of the construction life-cycle process (design, building, use, maintenance, repair/replace), and to different purposes within data workflow process (collection, storage, process, analysis, value). This study has also identified new potential strategies linked to the integration of the two technologies, by which BIM and AM would receive mutual benefits from implementation in the construction industry. Also identified during the cross-situational analysis are new value creation potentials triggered by innovative business models. However, discussion of these is outside the scope of this paper. They will be discussed in a future companion article, and which will focus on innovation and business models enabled by the adoption of AM in the building industry.

Table 7. Identified potentials and their characteristics[4]

Potential	**AM**	**BIM**	**Outcome**	**Life-cycle phase[5]**					**Data workflow[6]**					**Correspondence to references from scoping review**
				D	**B**	**U**	**M**	**R**	**C**	**S**	**P**	**A**	**V**	
1	S1 O4	S10	AM_O4 + BIM_O5	✓	✓						✓	✓	✓	(Tay et al., 2017, Correa, 2016)
2	O3	S2 S6 S7	AM_O3 (extended opportunity)			✓	✓				✓	✓	✓	
3	O2 W3 W2	S5 S6	AM_O2	✓	✓				✓	✓	✓	✓	✓	
4	S2	S1 S9	AM_O7	✓	✓							✓	✓	(Tay et al., 2017)
5	S2	S3 S9	AM_O9	✓	✓							✓	✓	
6	W4	S2 S5 S9	BIM_O1	✓	✓				✓	✓	✓	✓	✓	(Tan, 2018, Davtalab et al., 2018)
7	W7	S5 S6 S7	BIM_03	✓	✓	✓	✓	✓	✓	✓			✓	(Tay et al., 2017, Davtalab et al., 2018, Tan, 2018)
8	T2 T3 T4 T5	S5 S6 S7 T2 T5	BIM_O4	✓					✓	✓	✓	✓	✓	
9	S2 S4	S1 S9	BIM_O6	✓	✓	✓	✓	✓			✓	✓	✓	(Sakin and Kiroglu, 2017, Lu et al., 2016, Ding et al., 2014, van der Zee et al., 2014, Subrin et al., 2018, Davtalab et al., 2018, Perkins and Skitmore, 2015)
10	O10	O7 W7 W9	AM_T7 + BIM_T6 + BIM_T1										✓	
11	S3 W1	S1 W10	new opportunity	✓	✓									
12		O2	new opportunity	✓									✓	

[4] The abbreviation in the second, third and fourth columns refer to the SWOT analyses as shown in Table 5 and Table 6

[5] Life-cycle phase: **D**esign – **B**uilding – **U**se - **M**aintenance – **R**epair and Replace

[6] Data workflow: **C**ollection – **S**torage – **P**rocess – **A**nalysis - **V**alue

The potentials identified in this study are further elaborated as follows:

Potential 1 – Design optimisation

The combination of BIM and AM offers an opportunity to achieve a seamless digital workflow from design (BIM) to production (AM). Digital design permits the form-finding optimisation of new structures, while digital production enables the manufacturing of complex geometries at no extra cost. In addition, AM has less need of formwork and can accommodate design change or more rapid change management as part of the final output without incurring the same high level of losses associated with other, more conventional, processes (Tay et al., 2017).

Potential 2 – A digital life-cycle for additive manufactured concrete structures

Concrete structures built by AM will benefit from an integrated digital workflow from design to production, and throughout the entire life-cycle process. Currently, additive-manufactured concrete structures are young in age, so there exists little knowledge about their durability. They may require continuous monitoring. This phase can benefit from the digital scheduling, planning and documentation functions enabled by BIM and the interoperability with other technologies that facilitates autonomous monitoring.

Potential 3 – New concrete materials

A digital BIM platform will support the documentation of materials properties and performance during the design, production and operation phases, and in doing so will enable a more thorough data analytic approach to performance evaluation of the different materials. It is therefore expected that the data framework provided by BIM models will become a driver for the development of new concrete materials.

Potential 4 – Safer construction environments

Safety in the construction sector remains a major problem in the light of the high rates of fatalities and injuries involved (Zhang et al., 2013). The implementation of AM and BIM may help reduce the latter. On the one hand, tools offered by BIM implementations such as scenario planning, HSE compliance checking, clash detection and visual communication enhance our opportunities to detect and design-out health and safety risks from the outset. On the other, functions offered by AM, such as automation of construction, environment-independent construction, and robotic precision will reduce the levels of exposure incurred by on-site construction personnel. The integration of the two first-named functions may facilitate safer construction working environments and processes.

Potential 5 – Precision compounded multipart components as single products

AM may offer the opportunity to produce compounded multipart components as single products, which in turn will reduce assembly time. BIM is expected to enhance the robotic precision of additive manufacturing machines by offering substantial modelling and visualisation capabilities.

Potential 6 – More control over finishing

Coaster aggregates yield a rough finish on 3D-printed concrete surfaces. Due to their interoperability with artificial intelligence systems, BIM models can address this challenge by extracting and processing real-time data at the printing head at the time of concrete extrusion.

Potential 7 – Documented LCA (Life-Cycle Assessment)

BIM has emerged as a cloud data-rich, object-oriented and shared digital representation of a process extending across the entire life-cycle of a construction project. Models store valuable data related to whole-life costs, analysis and environmental data. BIM is thus expected to support the documentation of LCA for AM processes, currently an under-researched topic in the field of concrete structures (Labonnote et al., 2016).

Potential 8 – Acceleration of standardisation

BIM has been integrated into the construction industry at a much greater rate than other advanced technologies such as additive manufacturing. This has led to rapid advances in standardisation and maturity (Poljanšek, 2017). As a data-rich gathering platform, BIMs contain detailed information for the whole-life costs, analysis and environmental data together with detailed documentation of the different construction phases and compliance checking. Currently, concrete structures constructed through additive manufacturing are young of age and their application is steadily increasing with diverse technologies being employed in different countries. The availability of the such widespread information in a similar digital format as part of data-sharing and open systems can accelerate the gathering of the necessary and consistent data regarding the performance of additive manufacturing applications for concrete structures; and hence, it is expected to support and foster the completion of standardisation process for additive manufacturing.

Potential 9 – Automated assembly and coordination

Within a BIM model, entire virtual buildings are constructed with an accurate set of sub-models representing each construction phase. All of the model's elements have their precise geometry and properties. The next stage in the process involves a coordinated sequencing of steps, materials, and crews with the aim of achieving a more efficient construction process. The latter, complete with animations, facilitates the coordination of steps and processes, and delivers a predictable pathway to the expected outcome (Autodesk, 2018). AM is expected to further improve the construction process by upgrading it to robotic precision levels, thus enabling a very high degree of automated assembly and structure construction. Led by a BIM system, robots can also assist in other tasks such as welding and the polishing of complex forms (Sakin and Kiroglu, 2017). Moreover, AM robots themselves may benefit from BIM for calculation of the shortest, fastest and most cost-efficient nozzle trajectory paths (van der Zee et al., 2014).

Potential 10 – Job and skills transitions

The implementation of AM and BIM is expected to require changes in processes, working environments, and the establishment of new, in-house skills. This will introduce uncertainty into factors such as skills retention and salary policies. The second of these factors has traditionally acted as a barrier to the adoption of similar technologies, and the construction industry is regarded as one of the most conservative when it comes to the implementation of *Industry 4.0* (Agarwal et al., 2016). BIM and AM may receive mutual benefit by acting vigorously to promote change in the building sector. Both technologies favour easier skills transitions that are greatly dependent on the upstream involvement of academia and its ability to develop relevant BIM- and AM-related educational programmes.

Potential 11 – Shortening the building process

BIM and AM technologies modify the timeline of building processes. BIM requires a greater time investment upstream in order to build its models. The AM of concrete has often been criticised for requiring slow production processes (Bukkapatnam and Clark, 2007). However, both BIM and AM are expected to introduce universal reductions in the time taken to complete the building process, due both to the higher levels of planning efficiency offered by BIM, and the uninterrupted (24/7) workflows offered by AM.

Potential 12 – Digitally-driven professional networks

AM and BIM are both "digital" technologies. It is thus expected that the first enterprises to adopt any of these tools will be digitally driven, and thus will enable the embracement of the counterpart technology, either AM or BIM, more easily in their ecosystem. This in turn will contribute to a wider adoption of both technologies enlarging the network effect and subsequently, their value will increase as their user base increases. BIM and AM are thus expected to make substantial contributions to the digital transformation of the building industry by gathering people around various specific technologies.

4.3 General overview of identified potentials

A quilt plot showing the frequency and combination of identified potentials between life-cycle and data workflow processes is presented in Table 8. The results show that potential value creation is greatest when AM and BIM are integrated during the planning and building processes, focusing mainly on optimised design and autonomous construction. This correlates with the composition of the literature-based clusters derived from our bibliometric mapping (Figure 7), the correspondence observed between the references identified during the scoping review, and the potentials set out in **Error! Reference source not found.**Section 4.2. Note that data collection and storage are not identified as frequent potentials. Similarly, the life-cycle processes after building are characterised by fewer occurrences. One reason for this may be the very recent implementation of these two technologies, and the fact that most of the buildings employing these technologies are still young in age. As a consequence, their potentials may not be fully evident at this stage.

Table 8. Quilt plot showing the frequency and combination between the life-cycle and data workflow process for the potentials identified in this study[7].

		Life cycle					
		Design	Building	Use	Maintenance	Repair/Replace	
Data workflow	Collection	3; 6-8	3;6;7;9	7	7	7	3;6-9
	Storage	3; 6-8	3;6;7;9	7	7	7	3;6-9
	Process	1;3;6;8;9	1;3;6;9	2	2	-	1-3;6;8;9
	Analysis	1;3-6;8;9	1;3-6;9	2	2	-	1-6;8;9
	Value	1;3;5-12	1;3-6;9-11	2	2	-	1-12
		1;3-12	1;3-6;9-11	2;7	2;7	7	

Frequency based on colour:	*High*		*Medium*		*Low*

5 Conclusions

This study has completed a mixed-methods approach to the synthesis and aggregation of the literature discussing the integration of Building Information Modelling (BIM) in the Additive Manufacturing (AM) of concrete structures. Bibliometric mapping revealed a certain interest among the research community in integrating these two technologies, mostly in the field of concrete structures. However, progress is very slow compared to the rapidly developing interest in investigating each technology separately. The scoping review concluded that most of the literature discusses or conceptualises the integration of these two technologies at building scale, and that prototyping or PoC projects have only rarely been employed at different scales of structure.

The *TOWS² Matrix*, which is an advancement of the SWOT and TOWS Matrix, is here proposed and applied with the aim of exploiting joint value creation potentials by matching opportunities linked to the strengths, weaknesses and threats of the joint technologies. The *TOWS² Matrix* has enabled a systematic process to identify potential strategies linked to the integration of BIM and AM, by which the two technologies would receive mutual benefits from implementation in the construction industry. The

[7] The numbers refer to the indexed potentials presented in section 4.2. For example, [3; 6-8] refers to potentials 3, 6, 7 and 8.

method can be further applied for other topics where multi-dimensional capabilities are expected to be generated from the integration of more than two factors or categories, especially for emerging technologies.

The study identified 12 joint value creation potentials through the integration of BIM in AM for concrete structures. This integration is expected to generate value mostly during the planning and building process by facilitating more optimised designs, more control over finishing, precision compounded multipart components as single products, new materials, automated assembly and coordination, safer construction environments and shortening of the building process. It will also enable a digital life-cycle for additive manufactured concrete structures, a documented life-cycle assessment that supports data analytics and accelerate standardisation. Lastly, their adoption is expected to promote digitally-driven professional networks and job and skills transitions. This study is expected to trigger future research roadmaps and direct industrial applications when integrating BIM for AM for concrete structures.

Acknowledgments

References

ABDAL NOOR, B. & YI, S. 2018. Review of BIM literature in construction industry and transportation: meta-analysis. *Construction innovation,* 18**,** 433-452.

AGARWAL, R., CHANDRASEKARAN, S. & SRIDHAR, M. 2016. Imagining construction's digital future. *MCKINSEY INSIGHTS REPORT, MCKINSEY & COMPANY AND MCKINSEY GLOBAL INSTITUTE, JUN.*

ANTWI-AFARI, M. F., LI, H., PÄRN, E. A. & EDWARDS, D. J. 2018. Critical success factors for implementing building information modelling (BIM): A longitudinal review. *Automation in Construction,* 91**,** 100-110.

ARKSEY, H. & O'MALLEY, L. 2005. Scoping studies: towards a methodological framework. *International journal of social research methodology,* 8**,** 19-32.

AUTODESK. 2018. Building Information Modeling for the Win: Top 11 Benefits of BIM.

BATIPRINT3D. *INNOVATION FOR THE BENEFIT OF SOCIAL HOUSING* [Online]. Available: http://batiprint3d.fr/en/2017/09/21/innovation-for-the-benefit-of-social-housing/ [Accessed 2019].

BOOTH, A., PAPAIOANNOU, D. & SUTTON, A. 2011. *Systematic approaches to a successful literature review*, Sage.

BRYDE, D., BROQUETAS, M. & VOLM, J. M. 2013. The project benefits of building information modelling (BIM). *International journal of project management,* 31**,** 971-980.

BUKKAPATNAM, S. & CLARK, B. 2007. Dynamic modeling and monitoring of contour crafting—An extrusion-based layered manufacturing process. *Journal of manufacturing Science and Engineering,* 129**,** 135-142.

BUSWELL, R. A., DE SILVA, W. L., JONES, S. & DIRRENBERGER, J. 2018. 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research,* 112**,** 37-49.

COBO, M. J., LÓPEZ-HERRERA, A. G., HERRERA-VIEDMA, E. & HERRERA, F. 2011. Science mapping software tools: Review, analysis, and cooperative study among tools. *Journal of the American Society for Information Science and Technology,* 62**,** 1382-1402.

COBOD. *THE BOD: Europe's first 3D printed building* [Online]. Available: http://cobod.com/the-bod/ [Accessed 2019].

CORREA, F. R. Robot-oriented design for production in the context of building information modeling. ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction, 2016. 853-861.

DAVTALAB, O., KAZEMIAN, A. & KHOSHNEVIS, B. 2018. Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. *Automation in Construction,* 89**,** 13-23.

DING, L., WEI, R. & CHE, H. Development of a BIM-based automated construction system. Procedia Engineering, 2014. 123-131.

FOUNDATION, D. F. *THE OFFICE OF THE FUTURE: The world's first fully functional 3D printed building* [Online]. Available: http://www.officeofthefuture.ae/ [Accessed 2019].

ISIKDAG, U. & ZLATANOVA, S. 2009. A SWOT analysis on the implementation of Building Information Models within the Geospatial Environment. *Urban and Regional Data Management.* CRC Press.

JACKSON, S. E., JOSHI, A. & ERHARDT, N. L. 2003. Recent research on team and organizational diversity: SWOT analysis and implications. *Journal of management,* 29**,** 801-830.

JOBLOT, L., PAVIOT, T., DENEUX, D. & LAMOURI, S. 2019. Building Information Maturity Model specific to the renovation sector. *Automation in Construction,* 101**,** 140-159.

KIM, D. Y., CHOE, Y. & KIM, S. A. 2015. Implementing a digital model for smart space design: practical and pedagogic issues. *In:* IAMAN, A. & ESKICUMALI, A. (eds.) *International Conference on New Horizons in Education, Inte 2014.*

KOUCH, A. M., ILLIKAINEN, K. & PERALA, S. Key factors of an initial BIM implementation framework for small and medium-sized enterprises (SMEs). 35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things, ISARC 2018, July 20, 2018 - July 25, 2018, 2018 Berlin, Germany. International Association for Automation and Robotics in Construction I.A.A.R.C), Arcadis; Autodesk; et al.; Topcon; VHV Versicherungen; ZPP German Engineering.

LABONNOTE, N., RØNNQUIST, A., MANUM, B. & RÜTHER, P. 2016. Additive construction: State-of-the-art, challenges and opportunities. *Automation in Construction,* 72**,** 347-366.

LI, X., SHEN, G. Q., WU, P. & YUE, T. 2019. Integrating Building Information Modeling and Prefabrication Housing Production. *Automation in Construction,* 100**,** 46-60.

LU, B., TAN, M. J. & NAN, S. Z. 2016. A REVIEW OF 3D PRINTABLE CONSTRUCTION MATERIALS AND APPLICATIONS. *In:* CHUA, C. K., YEONG, W. Y., TAN, M. J., LIU, E. & TOR, S. B. (eds.) *Proceedings of the 2nd International Conference on Progress in Additive Manufacturing.*

MAHAMADU, A.-M., MAHDJOUBI, L., BOOTH, C., MANU, P. & MANU, E. 2019. Building information modelling (BIM) capability and delivery success on construction projects. *Construction Innovation*.

MOHER, D., LIBERATI, A., TETZLAFF, J., ALTMAN, D. G. & GROUP, P. 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS medicine,* 6**,** e1000097.

MX3D. *MX3D Bridge* [Online]. Available: https://mx3d.com/projects/bridge-2/ [Accessed 2019].

NIBS 2004. Building and Civil Engineering–Vocabulary–Part 1: General terms.

NIBS. 2019. *About the National BIM standard - United States* [Online]. Available: https://www.nationalbimstandard.org/ [Accessed 2019].

NORE, J. 2018. *RE: ACE BIM SWOT.*

PERKINS, I. & SKITMORE, M. 2015. Three-dimensional printing in the construction industry: A review. *International Journal of Construction Management,* 15**,** 1-9.

PETTICREW, M. & ROBERTS, H. 2008. *Systematic reviews in the social sciences: A practical guide*, John Wiley & Sons.

POLJANŠEK, M. 2017. Building Information Modelling (BIM) standardization. *European Commission*.

SAKIN, M. & KIROGLU, Y. C. 2017. 3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM. *In:* LITTLEWOOD, J. & HOWLETT, R. J. (eds.) *Sustainability in Energy and Buildings 2017.*

SALET, T. A. M. & WOLFS, R. J. M. 2016. POTENTIALS AND CHALLENGES IN 3D CONCRETE PRINTING. *In:* CHUA, C. K., YEONG, W. Y., TAN, M. J., LIU, E. & TOR, S. B. (eds.) *Proceedings of the 2nd International Conference on Progress in Additive Manufacturing.*

SMALL, H. 1997. Update on science mapping: Creating large document spaces. *Scientometrics,* 38**,** 275-293.

SMELOV, V., KOKAREVA, V. & MALYKHIN, A. 2014. Lean organization of additive manufacturing of aircraft purpose products. *International Journal of Engineering & Technology,* 6.

SOBOTKA, A. & PACEWICZ, K. 2016. Building Site Organization with 3D Technology in Use. *Procedia Engineering,* 161**,** 407-413.

SUBRIN, K., BRESSAC, T., GAMIER, S., AMBIEHL, A., PAQUET, E. & FURET, B. 2018. Improvement of the mobile robot location dedicated for habitable house construction by 3D printing. *Ifac Papersonline,* 51**,** 716-721.

TAN, K. The Framework of Combining Artificial Intelligence and Construction 3D Printing in Civil Engineering. MATEC Web of Conferences, 2018.

TANG, S., SHELDEN, D. R., EASTMAN, C. M., PISHDAD-BOZORGI, P. & GAO, X. 2019. A review of building information modeling (BIM) and the internet of things (IoT) devices integration: Present status and future trends. *Automation in Construction,* 101**,** 127-139.

TAY, Y. W. D., PANDA, B., PAUL, S. C., NOOR MOHAMED, N. A., TAN, M. J. & LEONG, K. F. 2017. 3D printing trends in building and construction industry: a review. *Virtual and Physical Prototyping,* 12**,** 261-276.

TECHNOLOGIES, A. C. F. O. A. M. & TERMINOLOGY, A. C. F. O. A. M. T. S. F. O. 2012. *Standard terminology for additive manufacturing technologies*, ASTM International.

TEIZER, J., BLICKLE, A., KING, T., LEITZBACH, O., GUENTHER, D., MATTERN, H. & KONIG, M. 2018. BIM for 3D Printing in Construction. *Building Information Modeling.* Springer.

TIBAUT, A., BABI, N. U. & PERC, M. N. Integrated Design in Case of Digital Fabricated Buildings. SBE16 Tallinn and Helsinki Conference; Build Green and Renovate Deep, 2016, October 5, 2016 - October 7, 2016, 2016 Tallinn, Estonia. Elsevier Ltd, 212-217.

UHM, M., LEE, G. & JEON, B. 2017. An analysis of BIM jobs and competencies based on the use of terms in the industry. *Automation in Construction,* 81**,** 67-98.

VAN DER ZEE, A., DE VRIES, B. & SALET, T. 2014. *From rapid prototyping to automated manufacturing*.

VAN ECK, N. & WALTMAN, L. 2009. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics,* 84**,** 523-538.

WANG, X. & CHONG, H.-Y. 2015. Setting new trends of integrated Building Information Modelling (BIM) for construction industry. *Construction Innovation,* 15**,** 2-6.

WEIHRICH, H. 1982. The TOWS matrix—A tool for situational analysis. *Long range planning,* 15**,** 54-66.

ZHANG, S., TEIZER, J., LEE, J.-K., EASTMAN, C. M. & VENUGOPAL, M. 2013. Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Automation in Construction,* 29**,** 183-195.

ZHAO, X. 2017. A scientometric review of global BIM research: Analysis and visualization. *Automation in Construction,* 80**,** 37-47.

ZHENG, X., LU, Y., LI, Y., LE, Y. & XIAO, J. 2019. Quantifying and visualizing value exchanges in building information modeling (BIM) projects. *Automation in Construction,* 99**,** 91-108.

Response to the reviewers

We thank the reviewers for their time and valuable comments/suggestions. The references have been updated and checked thoroughly to meet the journal requirements.

Reviewers Comments to Author	**Authors Response to Reviewers Comments**
Reviewer 1	
It seems there was a problem with the referencing software. Please check and fix this problem. (Footnotes of page 16 – footnote 5; and Section 4.3) Also, in your references section, some of the websites does not have the last access time, and are only being mentioned as "Accessed". - "MX3D Bridge", and "National Institute of Building Science 2019". The referencing style and order of elements are not followed for some references. Please review the referencing guide of the journal, review the whole section, and fix all such problems. i.e. Ding et al. 2014- the year came after publication name. Kouch et al. (2018) Tan 2018 Tibaut et al. (2016)	The references and footnotes have been updated and checked thoroughly to meet the journal requirements.