SOCIAL NETWORK ANALYSIS IN RESEARCH ON DIGITALIZATION IN SUSTAINABLE BUILT ENVIRONMENT: A REVIEW OF RESEARCH CCOMPLISHMENTS AND FUTURE RESEARCH CHALLENGES.

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ABSTRACT

This paper presents a research agenda for Social Network Analysis (SNA) in Digitalization in Sustainable Built Environment research (DSBE). The paper contains a description of SNA, and reviews the use of SNA in DSBE research. Also, the paper identifies future research challenges that SNA can help resolve. A literature review of DSBE finds that of 506 articles in 36 journals, only 1 article includes SNA. This is surprising, given the growing interest in SNA in digitally related fields. We review the 506 DSBE articles and analyze how SNA can contribute to the field. To understand how SNA can be used in DSBE research, we also analyze how SNA has been applied in Digitalization in Built Environment research that is not focused on sustainability. Findings are that SNA can be a useful and powerful tool, because it can help in analysis of how multiple actors interact, which is a common theme in built environment research. An example is that architects, contractors, and developers are separate actor groups that can improve sustainable solutions through networked cooperation. Another area in which SNA can advance research is in the study of how actor networks of companies or people relate to networks of data or physical buildings or sensors. An example is that actors may change their behavior based on sensor data, and SNA can study sensor data networks and actor behavior networks as interconnected layers. Methodological advances are key to advancing research to meet sustainability challenges. Specifically, SNA can make it possible for the built environment area to advance sustainability and digitalization research, because SNA has a rich array of empirical and conceptual tools for the study of networks.

KEYWORDS:

Social Network Analysis; Sustainability; Digitalization; Built Environment; Literature Review

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INTRODUCTION

Engineering Project Organization needs to develop in order to meet future real world challenges, such as sustainability, pandemic, and changing world order. For instance, buildings, construction and transportation are all major CO2 emitters, and they are integral parts of the built environment, which makes sustainability in the built environment sector central to meet the global climate challenge. While numerous efforts are needed, methodological advances are essential, because they are important tools to meet future challenges. Because future challenges require that more kinds of actors are connected, we see network research methods as foundational to meet future challenges. This paper focuses on the use and potential contributions of Social Network Analysis (SNA) research methods in a research area at the intersection of digitalization, sustainability and built environment research. We define the research area by using a structured literature review approach, and present how SNA can contribute to this research. Therefore, the contribution of this paper is a methodological contribution in the research field.

Today, digitalization and sustainability are megatrends that have a profound impact on all industries. The research area focusing on the built environment and digitalization crosses many disciplinary and industry boundaries, and as this field is emerging, we need to first define it. To start with the built environment concept, it has been defined as "*the human-made space in which people live, work, and recreate on a day-to-day basis*" (Lee et al. 2017) (Figure 1). This definition is very broad and it is an overarching concept for the real estate, construction and urban planning areas. We will narrow down the scope of this paper by selecting sustainability and digitalization as defining criteria for our topic of study.

Turning to digitalization, it is broadly defined as "*the integration of multiple technologies into all aspects of daily life that can be digitized*" (Gray and Rumpe 2015), and it takes many forms in the context of built environment research. Examples of progress made by digital technologies to date are digitally controlled energy consumption in buildings (Guo et al. 2018), 3D models for sustainable construction (Liu et al. 2019) and digital sustainable facility management (Akinade et al. 2018).

Digital technologies are distributed and generative by nature (Yoo et al. 2012; Tilson et al. 2010), and these characteristics distinguish digital technologies from other technologies. Because of these characteristics, digitalization requires development of new models for analysis, and new research methods. For example, as digitalization makes it possible to change many parts of the built environment simultaneously, there is a particular need for methods and models that can consider the influences of these advanced technologies to various built environment processes and users. Furthermore, such methodological developments are essential to advance theory in a field, because methodological advances make it possible to increase the understanding of empirical phenomena of relevance to a research field (Rosenberg 2018; Fellows and Liu 2015; Pomponi and Moncaster 2017). As such, methodological advances can help address the grand challenges of Engineering Project Organization Research (Sakhrani et al. 2017). Within the universe of research that concerns digitalization and built environment, this paper focuses on sustainability research, and

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this is the final narrowing of the scope of our study. Sustainability, like built environment, is a concept with a very broad scope, and the United Nations defined it as "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*". The present research focuses on the intersection of built environment, digitalization, and sustainability. While each of these areas are broad in scope, the intersection is not, and we define this intersection as a research area which we call *Digitalization in Sustainable Built Environment (DSBE*) research.

This article suggests that Digitalization in Sustainable Built Environment research could be advanced by a method that has long traditions, namely Social Network Analysis. A social network is a set of nodes connected by one or more relations, and SNA *is a research perspective that takes these relations and patterns they form as a unit of analysis* (Marin and Wellman, 2011). The benefits of SNA is that it studies how actors connect to one another, and it also allows for the analysis of how various forms of content forms the basis for connections between actors (Scott 2013). Therefore, it is well suited for research on actor networks and distributed digital technologies. Today, there is considerable development in SNA conceptualization and measurement, making it a potentially important contributor to the advancement of our understanding of Digitalization in Sustainable Built Environment.

Therefore, this article concerns literature on Digitalization in Sustainable Built Environment, an area that is in rapid growth and thus in need of a literature review. More particularly, the focus is on the use of SNA in this literature. We analyzed the literature, but found that only 1 article in a sample of 506 DSBE articles use SNA. There is therefore a need to present SNA, its potential accomplishments, and future research challenges, to researchers. In order to analyze how SNA is used in DSBE literature, we searched a broader sample of 3114 articles on Digitalization in Built Environment (DBE) and found 23 SNA articles.

Consequently, *the purpose of this paper is to analyze the potential for contribution of SNA to Digitalization in Sustainable Built Environment research*. Also, to analyze the SNA and DSBE articles, a framework of central themes in Digitalization in Built Environment research is developed.

The paper is structured so that it starts with a description of SNA, whereafter the method for literature review is described. After the method section, results of an in-depth analysis of the 23 SNA articles is presented, which is followed by an analysis of how SNA can potentially contribute to central themes in DSBE research. The concluding section addresses how SNA can aid in the quest to resolve the grand challenges of Engineering Project Organization Research (Sakhrani et al. 2017).

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Key Concepts	Definition
Built Environment (BE)	"the human-made space in which people live, work, and recreate on a day-to-day basis" (Lee et al. 2017)
Digitalization	"the integration of multiple technologies into all aspects of daily life that can be digitized" (Gray and Rumpe 2015)
Sustainability	"meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations)
Digitalization in Built Environment research (DBE)	A research area at the intersection of Built Environment and Digitalization research
Digitalization in Sustainable Built Environment research (DSBE)	A research area at the intersection of Built Environment, Digitalization and Sustainability research
Social Network Analysis (SNA)	A social network is a set of nodes connected by one or more relations. SNA is a research perspective that takes these relations and patterns they form as a unit of analysis. (Marin and Wellman, 2011)

Figure 1. Key concepts and definitions

SOCIAL NETWORK ANALYSIS

Social network analysis originated in sociological studies of relations between humans, and developments have resulted in both methodological advances and a rich conceptual development (Wasserman and Faust 1994). The SNA method and theory later found a number of applications outside of social science, for instance in mathematics, biology, computer science, and medicine. An example of the benefits that SNA can bring is from health care, where disease transmission has been studied based on behavioral personal networks and social networks (Luke and Harris 2007). The benefit of SNA in the study of disease transmission is that it can study the interaction of social networks and physical behavioral networks, which has advanced contact network research on how diseases such as HIV/AIDS and Covid-19 are spread (Prem et al. 2020). Along with methodological advances, SNA has developed a rich set of concepts, and these have contributed towards advances in conceptual development, theory, and modelling in a wide array of sciences (Dickison et al. 2016)

Social network analysis generally concerns a set of nodes and the ties that connect them. The main reason for studying networks is an interest in how connections between nodes influence behaviors and how behaviors lead to certain structures, which governs continued behavior (Scott 2013). The focus of SNA is thus on the structural aspects of networks, where actors and ties form patterns and structures within which there is content, or flow (Burt 1992; Scott 2013). Other network research focuses on relational

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aspects thatare more attitudinal, such as trust, cooperation, reciprocity, and long-term perspective (Gulati 1998), but SNA focuses on network structure, and argues that various forms of content flow in those structures. SNA is a research method that studies ties between nodes in networks, and these nodes are usually actors (Scott 2013, Borgatti et al. 2013). Actors (also called nodes) can be individuals or collective actors such as organizations or firms. Actors inhabit certain positions that yield them access to the contents that flow in the ties between the actors in the network. The actors can have multiple attributes, such as financial resources, legal status, patents, or geographical operations and location. The ties between the actors can also be defined in many ways, such as financial, regulatory, R&D, organizational, licensing and other commercial ties. An example of SNA is that flows in ties can reach a certain node at a certain time, but then continue flowing in subsequent time periods. The SNA network is structured over time by that actors' behavior at one point in time affects the actors' possibilities for continued tie attachment or dissolution in subsequent time periods (Owen-Smith and Powell 2004). In the network structuration, ties serve either as pipes for content or as governance mechanisms when resources such as legitimacy and acceptance flow through a network (Podolny 2001; Borgatti and Halgin 2011).

One of the advantages of SNA is that it presents a rich set of categories for the description of actors, ties, and networks. One of the most common network measure is *position*, meaning that "an actor's position in the network determines in part the constraints and opportunities that" the actor "will encounter and therefore identifying that position is important for predicting actor outcomes such as performance, behavior and beliefs" (Borgatti et al. 2013, p. 1). Position can be studied at three different levels: 1) the dyadic level in a relationship, 2) the actor's position in its own, ego- set network, or 3) actors' positions in relation to the whole network. An actor can have a *bridging position*, which refers to an actor who provides the only tie between two other actors, and the two networks are thus indirectly tied to each other through the actor that is in a bridging position.

Another measure is *indegree centrality*, which measures the number of ingoing ties to an actor, and thus defines how many other actors are tied to a focal actor. Its opposite is o*utdegree centrality,* which measures the out-going ties of the actor, and shows how many other actors the focal actor has connected to. The sum of these incoming and outgoing ties measures an actor's *local centrality,* and it is a measure of influence or importance of an actor in the local network. The *global centrality* on the other hand refers to an actor's centrality in the whole network and is a measure of the aggregated distance to all nodes in the network. All of these measures relate to an actor's position and how things either flow to the actor or from the actor. For instance, an actor that possesses scarce resources, is often central in the network. Access to the scarce resources of central actors will be limited for actors that are at a large *distance* to the central actors, and distance is defined as the minimum number of ties required to connect two actors. The *density or global density* is the number of ties connecting to the nodes in the network as a proportion of the total number of ties possible. Density can also be measured as *neighborhood density***,** which is a measure of the extent the direct ties are connected to each other. In a network with high density, many actors will have direct ties to each other. In

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terms of information flows, the same information will flow to most of the actors making it difficult to get novel information (Granovetter 1985). This type of density can exist in a *component*, which is a part of the network where the actors are tied only to each other. Components show the boundaries within the network.

There is a strong development of both theory and method in SNA in parts of the research community outside of BE (Scott 2013, Borgatti et al. 2013) and there is a corresponding development in software applications and measurements. Table 1 summarizes the discussion on SNA by presenting commonly used SNA network components and measures. We selected these measures as they are based on the fact that they are commonly used in the SNA literature (Scott 2013, Borgatti et al. 2013). The first four are network components; Actor, Tie, Node, and Edge are common components of SNA networks, and the other measures are common SNA measures that describe network structure.

Table 1. Description of selected SNA network components and measures.

Common SNA network components	**Description**
Actor	Conceptualization of actors as individuals, and collective actors allow for study within and between networks of actors. Actors can also be conceptualized as physical objects, such as sensors, buildings, factories, or CO2 emitting entities.
Tie	Measurement of tie strength between actors. Tie strength can be measured between actors of the same category, such as individuals, or actors of different categories, such as individuals and buildings.
Node	Study nodes that measure phenomena differentially, and how these different nodes relate to each other.
Edge	Different definitions of Edge of network can develop understanding of boundaries of different networks, and the role of those borders.
Common SNA measures	**Description**
Bridging position	Bridging positions within and between networks.
Distance	Can be used to add a differentiated set of measures to traditional data. Example is to combine sales data with interaction frequency.
Centrality	Differentiated measurement of an actor's position in a network. Actor centrality in different countries, firms or institutional settings.
Indegree	Differentiated measure of actor's centrality that can be used to measure actor position in innovation, knowledge, performance, and country networks.
Outdegree	Adds to research in combination with traditional measures, such outward resource flows, such as sales and investment. Measured as outward interactions, knowledge dissemination and inquiries.
Betweenness	Potential to measure different kinds of bridging positions between networks, such as bridging between institutions and businesses in national and international networks.

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Density	Can add to research by differentiated measures of different kinds of densities in different networks, such as institutional and business networks in intra and inter-firm networks.
Multilayer networks	Computes networks as layered networks and measures the relationship between layers.

METHODOLOGY

Today, there is a growing literature on research methods for making review articles, and this methodological literature distinguishes different types of review methods for different purposes. Most of these methodological articles state that it is important to be clear about the definition of what literature you are going to search, and the methods for searching within that literature (Webster and Watson 2002). When it comes to the use of search concepts, literature reviews usually differ depending on the extent to which they are confirmatory or exploratory.

The purpose of confirmatory literature reviews is to bring clarity to the definition, use, and relationships between concepts. The purpose of exploratory literature reviews is to develop research in new ways, for instance by the development of theory, model, framework. An example of an exploratory literature review is a grounded literature review, where the definition of what is included in the literature is subject to an iterative grounded theory search method that goes back and forth between what is included in the literature and the synthesis of the research (Wolfswinkel et al. 2013). Grounded literature reviews aim primarily to develop theory, frameworks, or generate models, but it can also lead to taxonomy.

A common recommendation is to combine exploratory and confirmatory literature search, by iterating between conceptually motivated search terms, and results found in the literature search. The researcher thereby selects theoretically motivated concepts, as in a confirmatory literature review, and then refines the concepts and searches again, based on the findings of the literature review, as in an exploratory literature search. This is sometimes referred to as a forward-backward search process (Webster and Watson 2002).

Literature search and analysis

For the purpose of this paper, the best suited method is a structured literature review, as it can systematically and comprehensively analyze research articles in the Digitalization in Built Environment and Digitalization in Sustainable Built Environment literature streams. Because the purpose of this study is to identify literature at the intersection of built environment, digitalization, and sustainability, the present research is a confirmatory literature review, with limited exploration within the selected literature. In such a review, clarity of definition of the literature, and clarity of the search terms are central for the validity and reliability of the literature review (Wilding et al. 2012).

The first step in the literature search was to distinguish the literature on Digitalization in Built Environment. Here, the literature is defined as research literature in refereed scientific journals that contain DBE research. The definition of DBE research is comprehensive, meaning that it does not

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include only the most cited articles, or prominent built environment journals, but instead includes any scholarly articles in the research area, as defined by our search protocol below.

First, to cover the area, we searched for the most suitable databases that include BE literature, and the result was that ABI inform Global / ProQuest and Business Source Premier / EBSCO together incorporate all of the BE journals. We also searched articles in SCOPUS and Web of Science core collection databases but found out that most of the BE journals were already covered in our sample, and therefore we did not include these databases to our search.

Second, as we aim at analyzing the potential for contribution of SNA to Digitalization in Sustainable Built Environment research, we needed a sample of articles that contain enough SNA articles. We did several searches with different keyword combinations and found that there are few SNA articles in the research that cover the intersection of digitalization, sustainability, and BE research. Therefore, we broadened the scope to include a large sample of articles on the subject areas in BE research. Because BE is an overarching concept for the real estate, construction, and urban planning areas, we chose the following search terms: 1) "Construction AND (Digital* OR build*)", 2) "Real estate AND digital*" and 3) "(Urban OR Built*) AND digital*" (Figure 2). During the process, we analyzed the results of the searches, and we found out that these keyword combinations produced a sample that is broad enough to contain multiple SNA articles, as well as many articles that focus on digitalization and sustainability. The search was done on the title, abstract and keywords of the articles. We extracted the literature sample from the databases on March 11, 2020, and removed duplicate values. The search produced 8990 articles from 1768 journals.

We acknowledge that 'digital*' as a search term is limited, as it does not cover articles that focus on digital technologies. As follows from our results we do get a good selection of the literature, and that makes it possible for us to draw conclusions on the potential contribution that SNA can make. However, future research could use other search terms of digitalization, and these could include specific technologies, such as BIM. On the other hand, our article selection contains a large selection of articles in the BE field. A broad definition of the literature was necessary to include enough SNA articles, and our further analysis, which is based on reading of the titles, abstracts, keywords, and methods sections, refined the selection, as we focused particularly on digitalization, sustainability, and research methods in this literature.

Third, to limit the number of articles for analysis, we selected the 3114 articles that are in the most central journals in the field (see table 2). This selection was based on a review of the journals' scopes by reading journal and article titles. The journals that were excluded are either not peer-reviewed academic journals, they are not related to BE research, or they have published few of the articles in the sample and are therefore not the most central journals in the field. The exclusion criteria resulted in a cutoff at 20 articles.

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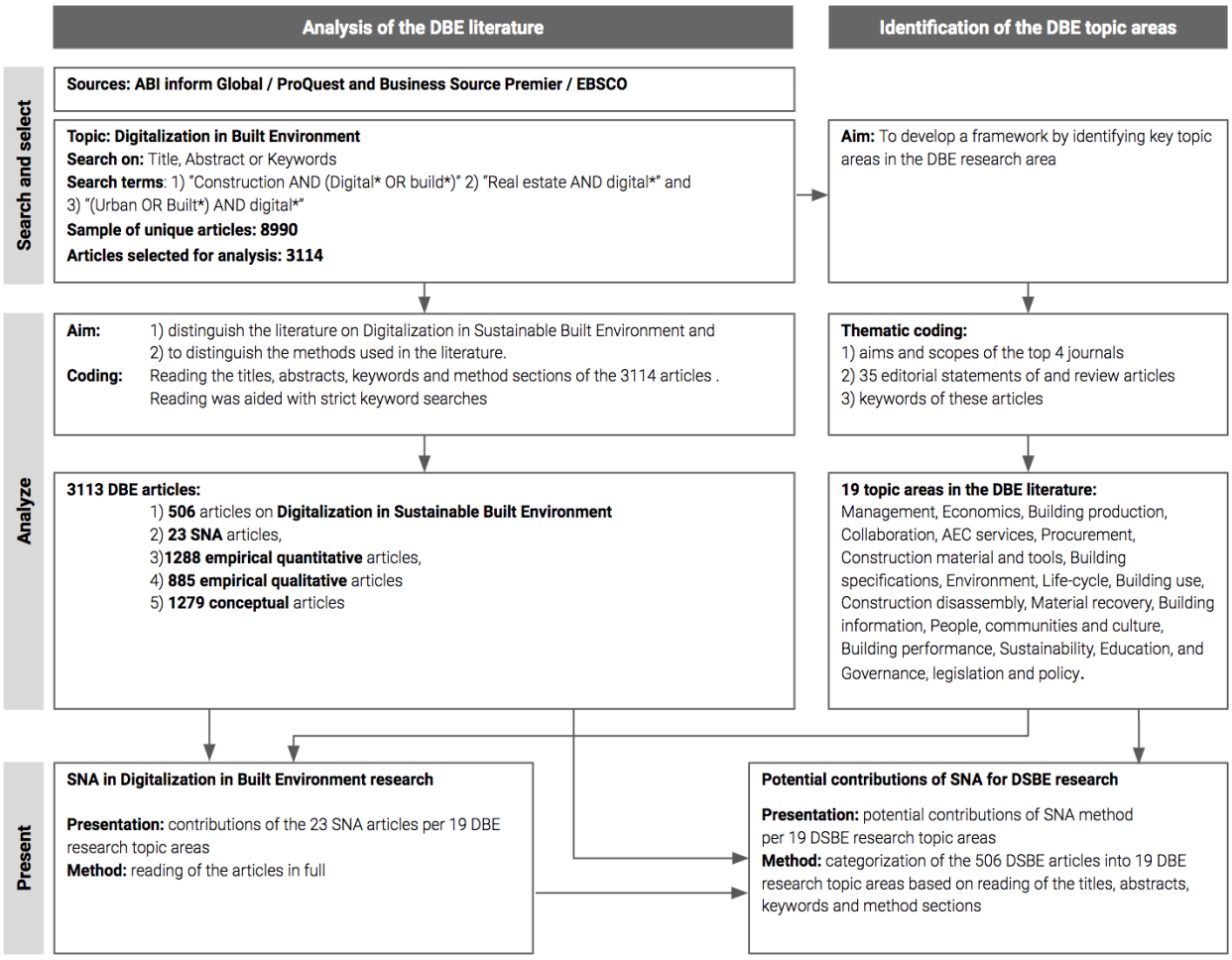

Figure 2. Literature search and selection

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Table 2. List of top 36 journals based on amount of Digitalization in Built Environment research articles published.

Rank	Journal title	Number of DBE articles
1	Construction Management & Economics	405
2	Journal of Construction Engineering & Management	393
3	Building Research & Information	317
4	Journal of Cleaner Production	299
5	Engineering Construction & Architectural Management	191
6	Journal of Management in Engineering	137
7	Cost Engineering	121
8	Energy Policy	98
9	Construction Innovation	91
10	International Journal of Project Management	84
11	Forest Products Journal	84
12	Structural Survey	83
13	Facilities	79
14	Habitat International	70
15	Building Services Engineering Research & Technology	52
16	Built Environment Project and Asset Management	46
17	Applied Thermal Engineering	45
18	Journal of Industrial Ecology	43
19	Organization, Technology & Management in Construction	38
20	Nexus Network Journal	37
21	Journal of Facilities Management	30
22	Environmental Science & Technology	30
23	Appraisal Journal	29
24	Journal of Financial Management of Property and Construction	28
25	Cities	27
26	Urban Studies	26
27	International Journal of Disaster Resilience in the Built Environment	26
28	European Journal of Operational Research	25
29	International Journal of Strategic Property Management	25
30	Project Management Journal	23
31	Computers in Industry	23
32	Planning Perspectives	22
33	Journal of Composites for Construction	22
34	Journal of Building Appraisal	22
35	Construction Economics & Building	22
36	Leadership & Management in Engineering	21
-	**Total number of articles analyzed**	**3114**

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The fourth step in the literature selection was to analyze the 3114 articles to (1) distinguish the literature on Digitalization in Sustainable Built Environment and (2) to distinguish the methods used in the 3114 articles. For this, we coded the articles based on topics and methods, and this was done by reading the titles, abstracts, keywords, and method sections of the 3114 articles. The aim of the reading was to confirm whether an article covered a specific topic or used a particular method.

We used the following search terms in strict keyword searches in the articles in order to aid reading: “digital*” OR "VDC" OR "Virtual design construction" OR "BIM" OR "building information modeling" OR "building information modelling" OR "geodesy" OR "geographic information" OR "GIS" OR "map projection" OR "georeferencing" OR "coordinate system" OR "lidar" OR "laser scanning" OR "photogrammetry" OR "UAV" OR "drone" OR "point cloud" OR "machine learning" OR "deep learning" OR "computer vision" OR "image recognition" OR "geodesy" OR "geographic information" OR "georeferencing" OR "map projection" OR “social network analysis” OR "ucinet" OR "pajek" OR "netminer" OR "nodexl" OR "gephi" OR "cytoscape" OR "event history" OR "regression" OR "structural equation modeling" OR "structural equation modeling" OR "lisrel" OR "qualitative comparative method" OR "R" OR "least square" OR "maximum likelihood" OR "maximum-likelihood" OR "logit model" OR "chi square" OR "chi-square" OR "X" OR "χ" OR "neural network" OR "analytic network process" OR "modeling" OR "modelling" OR "survey" OR "anova" OR "cluster analysis" OR "case study" OR "ethnography" OR "abductive method" OR "grounded theory" OR "action research". The selection of the search terms was partially exploratory and involved going back and forth between selecting the search terms and reading the articles in the literature to understand how content suited the search categorization. We also included search terms that were mentioned in the keywords of the articles, as well as keywords that are common in qualitative and quantitative methods textbooks.

With this search protocol, we identified that in the sample of 3114 articles, there are (1) 506 articles on Digitalization in Sustainable Built Environment, and (2) there are 23 SNA articles, 1288 empirical quantitative articles, 885 empirical qualitative articles and 1279 conceptual articles that do not use any empirical method or data (see table 3). The empirical methods are sometimes used in combination, and because of this a single article can appear in multiple method categories.

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Table 3. Categorization of articles in Digitalization in Built Environment research. A single article can contain several methods.

Categorization of articles	Quantity	Number of articles that use qualitative and quantitative methods in combination with SNA
Conceptual built environment research	1279	-
Empirical qualitative built environment research	885	In total 17 of the 885 (2%) articles use qualitative methods in combination with SNA: Case study: 16 articles Ethnography: 2 articles Action research: 1 article
Empirical quantitative built environment research	1288	In total 12 of the 1288 (1%) articles use quantitative methods in combination with SNA: Regression: 2 articles R: 2 articles Least square: 1 article Maximum likelihood: 2 articles Modelling: 5 articles Survey: 6 articles
Social network analysis	23	-
Total articles analyzed	**3114**	-

In order to make analysis of the use of SNA in Digitalization in Built Environment research and of the potential for contribution of SNA to Digitalization in Sustainable Built Environment research, we developed a framework by identifying key topic areas in the DBE literature. The process of identifying the topic areas was to compare three sources of information: 1) topic areas mentioned in the aims and scopes of the top four journals in the DBE literature (measured by the number of publications in the sample), 2) topic areas mentioned in the 35 editorial statements of and review articles published in 2018 - 2020 in these journals, and 3) keywords of these editorial and review articles.

The comparison of these different sources of information was done by grouping pieces of information together. First, we read through the 35 editorial and review articles and listed topic areas that were mentioned as important for future research. Second, we read through the aims and scopes of the four journals, and listed topic areas mentioned in these texts. Third, we listed the keywords of these 35 articles into a keyword frequency table. After this we had a list of 48 topic areas and 127 keywords. We systematically combined topic categories that concerned similar topics in a thematic coding process (Gibbs, 2007). For example, we combined topic areas of "Production of the built environment", "Other construction related value-adding activities" and "On-site production" into a higher-order thematic category "Building production". We concluded that 19 broad topic categories cover the research interests in DBE research. Finally, we compared the list of themes with the list of most frequent keywords (frequency>1) to check if the keyword topics are included in the topic

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categories and concluded that no new categories emerged from these keywords.

We therefore identify the following 19 topic areas in the DBE literature: Management, Economics, Building production, Collaboration, AEC services, Procurement, Construction material and tools, Building specifications, Environment, Life-cycle, Building use, Construction disassembly, Material recovery, Building information, People, communities and culture, Building performance, Sustainability, Education, and Governance, legislation and policy.

We used these 19 DBE research topic areas to categorize the 23 SNA articles and the 506 sustainability articles. The categorization of the SNA articles was based on reading the articles in full, and the categorization of the sustainability articles was based on reading of the titles, abstracts, keywords, and method sections of the 506 articles.

Therefore, as the 19 DBE topic areas represent the full spectrum of DBE research, and the literature search protocol provides an extensive search, the analysis that follows presents a comprehensive picture of use of SNA in Digitalization in Built Environment research. That in turn provides a basis for analyzing the potential for contribution of SNA to Digitalization in Sustainable Built Environment research.

SNA IN DIGITALIZATION IN BUILT ENVIRONMENT RESEARCH

This section presents an analysis of the 23 SNA articles that were recognized in the literature. First, the growth of SNA use in the literature and the journals that have published SNA literature are presented. Second, the analysis of the topics and methods of the SNA articles is presented. Finally, an analysis of the accomplishments of the 23 SNA articles, and the future research areas put forth in these articles, is presented.

Growth of SNA use in the DBE research and journals that have published SNA literature

The first of the 23 SNA articles was published in 1995 (Loosemore 1995), second in 2001 (Thorpe and Mead, 2001), third in 2006 (Pryke and Pearson 2006), and the rest (20 articles) between 2011 and 2018, indicating that interest in using SNA in DBE research has only recently emerged (see figure 3). The small number of SNA articles is surprising, as Loosemore pointed out already in 1995 that while SNA has been recognized as a useful method in other fields, its use for construction management research remains underexplored. Similar reflections about the usefulness of the SNA method for DBE research have been made in most of the 23 SNA articles.

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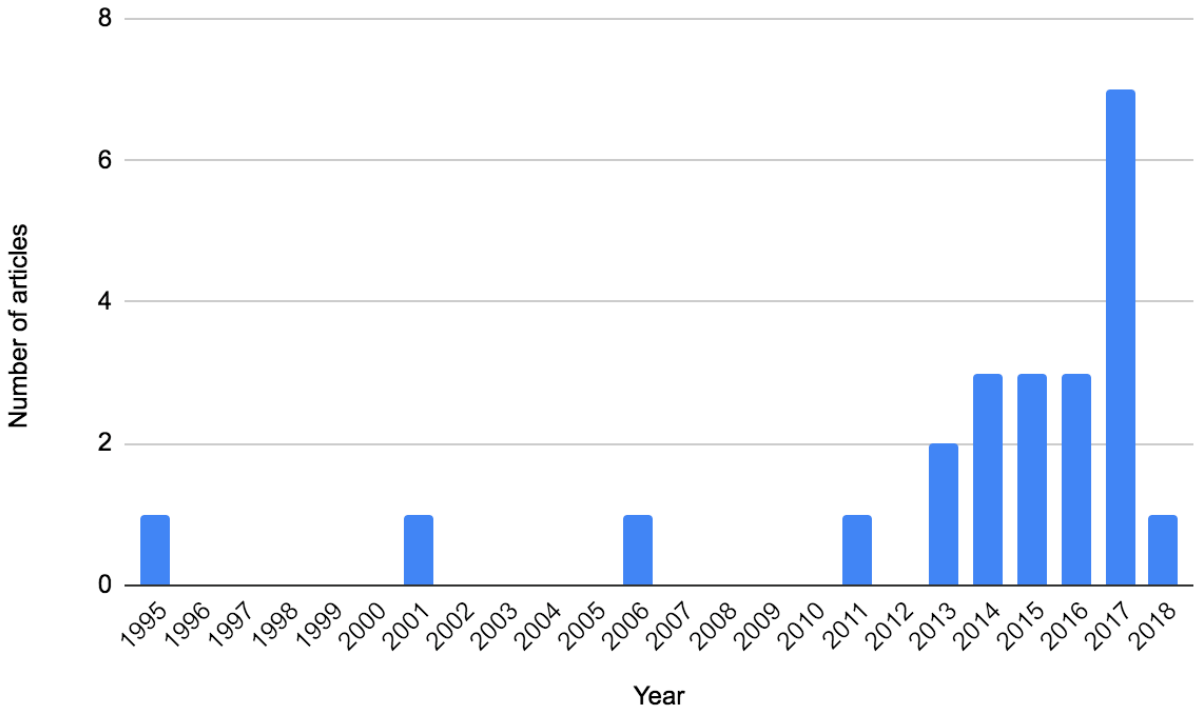

Figure 3. Number of SNA articles per year

The journals that have published SNA articles on DBE are Journal of Management in Engineering (7 articles), Journal of Construction Engineering and Management (5), Construction Management and Economics (4), Building Research and Information (2), Engineering Construction and Architectural Management (1), Habitat International (1), International Journal of Project Management (1), Journal of Cleaner Production (1) and Structural Survey (1).

The fact that SNA articles are spread across many journals suggests that these scholarly contributions do not reach the same academic audience. Also, a low number of SNA articles in those journals that have previously published SNA research might indicate that other authors have not picked up on the method that has been introduced in the journal, despite the SNA researchers have found the method useful and have suggested further use of the method. Therefore, most likely, this dispersion of scholarly contributions hampers the adoption of SNA in DBE research, as a critical mass of SNA-adept researchers, reviewers and readers has not been reached.

What topics do the 23 SNA articles cover?
The 23 SNA articles cover the 19 DBE topic areas only to a limited extent (note that one article can contribute to several topic areas). The topics of Building production (21 articles) and Management (15) account for most articles, and these topic areas overlap to a significant degree, as all of the Management articles concern managerial questions related to Building production.
In the Management topic area, two papers have used SNA to identify project-team level performance factors. First, Zhang et al.

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(2013) use various SNA measures in a case study to investigate sharing of tacit knowledge in building project teams, and by identifying knowledge flows and network structures, they argue that sharing of tacit knowledge can lead to a better team flexibility and increase in team's dynamic capabilities. Second, Solis et al. (2013) use SNA methods in a case study to identify characteristics of high performing project teams.

Further, six papers in the Management topic area have focused on coordination and performance in construction projects. Loosemore (1995) presents a case study, which investigates communication and behavioral issues in problem-solving processes in construction projects; Dogan et al. (2015) use degree, betweenness, and closeness centrality measures for monitoring the coordination performance of project participants; and Wambeke et al. (2014) measure task variation and project performance by using SNA and variation analysis. Others have focused on knowledge transfer practices in sustainable office building projects (Schöpfer et al. 2017), coordination productivity and information exchange patterns in BIM-based projects (Park and Lee, 2017) and workflow planning systems in construction projects (Priven and Sacks, 2015).

Similarly, five of the papers in the Management topic area focus on stakeholder networks related to construction projects: Boutilier and Zdziarski (2017) use SNA for quantifying stakeholders' issues and concerns related to construction projects; Teo and Loosemore (2017) analyze community-based protest groups as project stakeholders; Papadonikolaki et al. (2015) analyze information flows in construction supply chain, and propose a Building Information Management (BIM)-based model as an integrator of information flows for construction; Keung and Shen (2017) analyze how contractors' networks impact their competitiveness, and fifth, Li et al. (2016) use SNA to analyze stakeholder-associated schedule risks in a prefabrication housing production supply chain, and propose that BIM can be used to mitigate the schedule risks by facilitating stakeholder communication. Also, two of the articles focus on a broader perspective of construction industry networks: Lee et al. (2016) suggest an industry network-based methodology to analyze firms' competitiveness; and Pishdad-Bozorgi et al. (2017) use network analysis to identify practices that are most central in flash-track projects.

Out of the 21 articles in the Building production topic area, only 6 are not directly related to managerial questions. Still, four of these are also focused on networks and stakeholders in construction industry: Pryke and Pearson (2006) study financial incentives in construction project coalitions; Teo and Loosemore (2014) study community-based protests and focus on the role of core group members in sustaining the protests against construction and engineering projects; Cao et al. (2017) study how the micro level mechanisms and macro level structures of a collaborative BIM-implementation network evolve over time in a construction project; and fourth, Cao et al. (2018) make a link between the structural characteristics of a project-based interfirm collaboration network and organizational competitiveness. Furthermore, Zhou and Irizarry (2016) use SNA measures such as average degree, average path length, diameter, clustering coefficient, and betweenness centrality to analyze causation between events in a subway construction accident; and Thorpe

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and Mead (2001) study the role of project websites in project communication.

The topic areas of Collaboration (7), Building information (5), People, communities, and culture (4), Governance, legislation and policy (2), Sustainability (1) and Economics (1) have received only a few articles. Some of the aforementioned articles concern also these topics and two of the 23 SNA articles do not concern Building production or Management. The articles by Cao et al. (2017), Cao et al. (2018), Li et al. (2016), Park and Lee (2017), and Papadonikolaki et al. (2015) focus on Building information, analyzing BIM related networks; the articles by Boutilier and Zdziarski (2017), Teo and Loosemore (2014; 2017) and Larsen (2011) take perspectives related to People, communities and culture; and the articles by Pryke and Pearson (2006), Dogan et al. (2015) and Li et al. (2016) concern Collaboration related to building project stakeholder networks. Further, only two of the articles (Pryke and Pearson 2006; Lin and Tan 2014) concern Governance, legislation and policy, one article (Schröpfer et al. 2017) concerns Sustainability and one (Pryke and Pearson 2006) concerns Economics. Further, the topics of AEC services (0), Procurement (0), Construction material and tools (0), Building specifications (0), Environment (0), Life-cycle (0), Building use (0), Construction disassembly (0), Material recovery (0), Building performance (0) and Education (0) have not received any SNA articles.

Therefore, the 23 SNA articles have paved the way for SNA research in DBE literature, but only to a limited extent: a small number of articles in a topic area, or their absence altogether, indicates areas where SNA have yet to make contributions. Still, within the topic areas, where SNA articles are found, the articles cover a range of organizational topics and actors related to the DBE industry. Particularly, the authors have found SNA to be a useful method for research concerning organizational or interorganizational relationships and structures, such as networks, stakeholder groups or communities, but on the other hand, SNA has been used for non-social structures, such as events related to construction accidents (Zhou and Irizarry 2016), which demonstrates how SNA can be used also for non-organizational research. Also, in all of the 23 SNA articles, the authors suggest that use of SNA methods have been either a novel approach to collect and analyze empirical data in the research context, or that their approach offer an entirely novel contribution to the methodological development in the field. Therefore, the 23 SNA articles demonstrate that SNA methods are suitable for different types of DBE research.

What methods is SNA used in combination with?

Table 3 shows that this paper presents an analysis of 3114 DBE research articles, of which 1279 are conceptual articles, 885 are empirical qualitative articles, 1288 are empirical quantitative articles and 23 are empirical SNA articles. Analysis of the SNA articles show that in total 17 of the SNA articles (74% of the 23 SNA articles) use SNA measures in combination with qualitative research methods, that is: case study approach (16 articles, 70%), ethnography (2, 9%) and action research (1, 4%). Further, 12 of the SNA articles (52%) use SNA measures in combination with quantitative research methods, that is: regression (2, 8%), R (2, 8%), least square (1, 4%), maximum likelihood (2, 8%), modelling (6, 26%) and survey (6, 32%). Also, 22 out of 23 SNA articles (96%) use either quantitative and qualitative methods, or both, in combination with SNA measures;

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in other words, only one of the 23 articles is solely based on SNA method. This analysis indicates that the authors have found SNA as a useful method for mixed method research articles.

Further, Table 4 provides a break-down analysis of the methods used in the 23 SNA articles, in the 1288 quantitative articles and in the 885 qualitative articles. In the quantitative articles section, most popular methods have been survey (774 articles, 60% of the quantitative research articles), modeling (399, 31%) and regression (381, 30%), while other quantitative methods have been used in 866 (67%) articles. Respectively, in the qualitative articles section, most popular methods have been case study (849 articles, 96% of qualitative research articles), grounded theory (39, 4%) and action research (35, 4%), while ethnography have been used in 19 (2%) articles and abductive method or qualitative comparative method not at all. Also, examples in the 23 SNA articles show that SNA is a suitable method both for positivistic (f.e. Cao et al. 2018; Lee et al. 2016) and interpretivist (f.e. Teo and Loosemore 2014; 2017) research.

These analyses presented in Table 3 and Table 4 suggest that, due to the flexibility of the SNA method, SNA could provide additional methodological or theoretical insights to the 885 qualitative DBE articles, or to the 1288 quantitative DBE articles. Further, as a theoretical perspective, SNA could provide concepts to support the 1279 conceptual DBE articles. Currently SNA contributes only to 2% of the qualitative articles and to 1% of the quantitative articles.

On the other hand, a strict keyword search on the titles, keywords and abstracts of the 3114 DBE research articles shows that the search term “network” appears in 168 articles (5%), the search term “social” appears in 363 articles (12%) and that the search terms “organization” OR “organisation” appear in 422 articles (14%); and one of these search terms appear in 826 articles (27%) in total. This gives an estimate of the share of DBE literature, where SNA measures could be a natural alternative for a method choice. Therefore, there is a lot of potential for SNA in various forms of future empirical and theoretical DBE research.

Also, Table 4 provides a closer look on the methods and software packages used in the 23 SNA articles. The most popular software has been Ucinet (12 articles), while other software packages, such as Pajek (4), Netminer (2), Gephi (2), Nodexl (1) and Cytoscape (0) have received less attention. Each software package provides mostly similar functionalities, including visualizations and statistical analysis, but they are built for different purposes and thus are partly complementary. Most of the SNA software packages are freely available on the internet, and while some of them require more skills from the user, some are rather easy to use, even for those with no previous experience with SNA methods. For example, Dogan et al. (2015) argue that once the data is collected, in their case e-mail correspondence, analyzing networks with statistical measures using SNA software is easy. Therefore, those who have existing datasets could rather easily supplement the analysis with statistics and visualizations by using some of the SNA software.

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Table 4. Methods investigated and number of articles using the method. A single article can contain several methods.

Social Network Analysis		Quantitative methods		Qualitative methods	
Software	**Count**	**Method**	**Count**	**Method**	**Count**
Ucinet	12	Survey	774	Case study	849
Pajek	4	Modeling	399	Grounded theory	39
Netminer	2	Regression	381	Action research	35
Gephi	2	R	293	Ethnography	19
Nodexl	1	Anova	124	Abductive method	0
Cytoscape	0	Chi square/chi-square	120	Qualitative comparative method	0
		Least square	88		
		X/χ	88		
		Structural equation modeling	51		
		Neural network	35		
		Maximum likelihood	29		
		Cluster analysis	15		
		Logit model	9		
		Lisrel	9		
		Analytic network process	5		
		Event history	1		
Total	23		1288		885

What are the accomplishments and future research areas put forth in the 23 SNA articles?

The 23 SNA articles have made contributions only to 8 of the 19 DBE topic areas, and in these topic areas, the main focus has been on Building production and Management. Therefore, the proposals for future research mostly concern questions of management and networks related to construction projects, however, the authors of the 23 SNA articles also argue for further use of SNA in DBE research more generally. The table 5 provides a summary of the key accomplishments of the SNA articles in the DBE topic areas, as well as future research opportunities presented in the 23 SNA articles per each DBE topic area.

In the Management topic area (15 articles), the authors have focused on different units of analysis related to organizations and networks: these include teams (Zhang et al. 2013; Schröpfer et al. 2017; Solis et al. 2013), firms (Lee et al. 2016; Keung and Shen, 2017); and broader interorganizational structures, such as stakeholder networks (Boutilier and Zdziarski 2017; Teo and Loosemore 2017), supply chains (Papadonikolaki et al. 2015; Li et al. 2016) and construction projects (Loosemore 1995; Dogan et al. 2015; Wambeke et al. 2014; Pishdad-Bozorgi et al. 2017; Park and Lee, 2017; Priven and Sacks, 2015; Thorpe and Mead, 2001). Therefore, the key accomplishment of these papers is that they

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provide analysis and conceptualizations on various organization and network structures. Still, as these articles are largely focusing on building projects related management, they are limited in explaining management in other DBE topic areas, such as building life-cycle management or management related to building use or disassembly.

Further, in the Management topic area, the authors have pointed out opportunities for future research related to the specific topics of their papers. Dogan et al. (2015) call for research on management of shared resources, constraints, relationships and dependencies related to construction projects, and Wambeke et al. (2014) on management of variation in construction projects. Further, Li et al. (2016) call for research on stakeholder risk mitigation related to construction projects, and Priven and Sacks (2015) on coordination of workflows in construction projects. Others propose focus on actor behavior: Loosemore (1995) calls for research on linking structural network characteristics and behavior with problem-solving effectiveness during construction projects, and Teo and Loosemore (2017) on use of role theory to understand protest identity and behavior in construction protests. Another topic relates to further use of SNA: Papadonikolaki et al. (2015) propose further use of SNA based models for analyzing, supporting and improving BIM-enabled supply chains, and Boutilier and Zdziarski (2017) on integration of sustainable development goals into construction projects by paying attention to the social network structures.

Finally, several authors have proposed research related to competitiveness and collaboration: Lee et al. (2016) propose use of network characteristics to study firm competitiveness in the construction industry, Schröpfer et al. (2017) argue for research on the relation of knowledge networks and the performance of the built outcome, Solis et al. (2013) and Zhang et al. (2013) call for further studies on team and management performance in construction projects, and similarly, Keung and Shen (2017) on project network approach to competition and collaboration.

Therefore, research can be continued on the path indicated by these authors, but as mentioned, their focus is largely on management related to building projects, and thus there are various management related research opportunities in other DBE topic areas that could as well provide avenues for future research.

As the topic areas of Management (15) and Building production (21) are largely overlapping, the key accomplishments and proposed future research areas are largely the same. Still, six of the Building production topic area articles don't directly concern management. Rather, these concern project governance and financial incentives related to construction projects (Pryke and Pearson 2006), protest groups (Teo and Loosemore 2014), BIM implementation network dynamics (Cao et al. 2017), competitiveness based on the network structure (Cao et al. 2018), technology-supported project communication (Thorpe and Mead, 2001), and construction accidents (Zhou and Irizarry 2016). Therefore, the key accomplishment of SNA research in the Building production topic area is that the articles provide empirically novel analysis of problem-solving during building projects and of organizations and networks involved in building activities.

Respectively, the key future research areas put forth in the Building production topic

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area are closely related to the Management topic articles. Other than management related articles include, for example the article by Pryke and Pearson (2006), who have proposed research gaps on financial incentives within construction project coalitions, the article by Cao et al. (2017) on dynamics of collaborative networks for BIM implementation and variation of BIM implementation practices, and the article by Zhou and Irizarry (2016) on causal factors in construction accidents. Therefore, the future research areas proposed in the Building production topic are related to management of construction projects, project teams, and networks related to construction project stakeholders, as well as on construction protests groups, events in construction accidents and financial incentives related to construction projects.

In the DBE topic areas that have received less SNA articles, that is Economics (1), Sustainability (1), Collaboration (7), Building information (5), People, communities and culture (4), and Governance, legislation and policy (2), the accomplishments and proposed research areas are limited. First, in Economics, the article by Pryke and Pearson (2006) provides results, and calls for future research, on financial incentives related to project governance. Second, in the Sustainability topic area, the article by Schröpfer et al. (2017) provides analysis of knowledge flows in sustainable construction project, but in addition, Boutilier and Zdziarski (2017) call for research on integration of sustainable development goals into construction projects by paying attention to the social network structures.

Third, in the Collaboration topic area, the article by Pryke and Pearson (2006) provides SNA analysis on project coalition governance, the article by Dogan et al. (2015) on coordination performance in building design and construction, and Li et al. (2016) on coordination in a supply chain. Others have analyzed the role of technology in project collaboration (Park and Lee, 2017; Thorpe and Mead, 2001) and collaboration in project networks (Keung and Shen, 2017; Priven and Sacks, 2015). Therefore, the accomplishment in the topic area is to identify patterns on collaborations in construction networks. Future research proposals are related to stakeholder risk mitigation, project coordination, and mechanisms of how project-based relationship networks affect performance of design and construction organizations.

Fourth, in the Building information topic area, Cao et al. (2017), Cao et al. (2018), Li et al. (2016), Park and Lee (2017), and Papadonikolaki et al. (2015) provide analysis on networks related to BIM implementations. Further, Cao et al. (2017) propose research gaps on dynamics of collaborative networks for BIM implementation and variation of BIM implementation practices; Cao et al. (2018) for study of the mechanisms of how project-based relationship networks affect performance of design and construction organizations; Papadonikolaki et al. (2015) on use of SNA based models for analyzing, supporting and improving BIM-enabled supply chains; and Li et al. (2016) for research on stakeholder risk mitigation in building projects. Therefore, these papers provide a foundation for BIM related SNA research, but as these papers focus on BIM-related networks, they ignore many other technologies that are relevant for the Building information topic area.

Fifth, in the People, communities and culture topic area, Larsen (2011), Boutilier and Zdziarski (2017), Teo and Loosemore (2014)

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and Teo and Loosemore (2017) provide SNA analysis that link actor behavior to related innovation diffusion processes, stakeholder networks and communities in construction sector. Further, Larsen (2011) call for research on actor-level attributes, such as needs, actor thresholds, selective exposure, power, groupthink, peer pressure and contextual thresholds, which contribute to the innovation diffusion process, and Teo and Loosemore (2017) on use of role theory to understand protest identity and behavior in construction protests. Also, the authors remark that SNA can provide an excellent foundation for actor-network -level analysis. Sixth, in the Governance, legislation and policy topic area, the articles by Pryke and Pearson (2006) and Lin and Tan (2014) offer SNA-based insights on project coalition governance and public sector performance. They point out future research opportunities related to financial incentives within construction project coalitions and team, management and public sector performance. Therefore, in the topic areas where the articles are few, the overall contribution of the SNA research is limited, and depends a lot on the perspective of each individual article. This leaves many other topics in the respective categories uncovered. Finally, in the topic areas which have not received attention of SNA research, the accomplishments are yet to be made.

Table 5. Key accomplishments and future research opportunities per DBE research areas. A single article can contribute to several topics.

DBE topic areas	Number of SNA articles	Key accomplishments of the 23 SNA articles	Key future research opportunities put forth in the 23 SNA articles
Building production	21	Results on problem-solving during the building process and analysis of organizations involved in building activities.	Management of construction projects, project teams, and networks related to construction project stakeholders, as well as on construction protests groups, events in construction accidents and financial incentives related to construction projects.
Management	15	Analysis and conceptualizations on the intra- and inter-organizational management of projects and project stakeholder networks.	Use of SNA measures to identify management or team performance. Management of shared resources, constraints, relationships and dependencies. Research on knowledge sharing and flexibility in project teams. Relation between centrality index and managerial performance. Management of variation in construction projects.
Collaboration	7	Identification of patterns on collaborations in construction networks, e.g., in construction	Research on stakeholder risk mitigation in building projects. Further studies on the mechanisms of how project-based relationship networks affect

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		supply chains. Contributions in analyzing various stakeholder relationships.	performance of design and construction organizations.
Building information	5	Analysis of networks for BIM implementation and supply chain integration.	Dynamics of collaborative networks for BIM implementation and variation of BIM implementation practices. Use of SNA based models for analyzing, supporting and improving BIM-enabled supply chains. Stakeholder risk mitigation in building projects.
People, communities and culture.	4	Analysis related to innovation diffusion process, stakeholder networks and communities in the construction sector. Analysis of relation between actor behavior and network structures.	Research on the relation between structural network characteristics and actor behavior. Research on actor attributes that contribute to the innovation diffusion process. Use of role theory to understand identity and behavior in construction protests.
Governance, legislation and policy	2	Insights on project coalition governance and public sector performance.	Future research opportunities related financial incentives within construction project coalitions and team, management and public sector performance.
Sustainability	1	Mapping of knowledge flows in sustainable construction project teams.	Integration of sustainable development goals into construction projects by paying attention to the social network structures.
Economics	1	Results on financial incentives related to project governance.	Further studies on financial incentives within construction project coalitions.
AEC services	no articles	n/a	n/a
Procurement	no articles	n/a	n/a
Construction material and tools	no articles	n/a	n/a
Building specifications	no articles	n/a	n/a
Environment	no articles	n/a	n/a
Life-cycle	no articles	n/a	n/a
Building use	no articles	n/a	n/a
Construction disassembly	no articles	n/a	n/a

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Material recovery	no articles	n/a	n/a
Building performance	no articles	n/a	n/a
Education	no articles	n/a	n/a

POTENTIAL CONTRIBUTIONS OF SNA MEASURES FOR DIGITALIZATION IN SUSTAINABLE BUILT ENVIRONMENT RESEARCH

We selected 506 articles that concern Digitalization in Sustainable Built Environment. Of these articles, only 1 use SNA. That article concerns Management and Building production. Since only one article concerns SNA, there seems to be great potential for contribution by using SNA. Since SNA is specifically suited for network research, we went through the title, keywords, and abstract of each of the 506 DSBE articles, and found that 32 of them mention the word network. The distribution of the word network is such that Management, Building production and Environment are the DSBE topic areas with the highest number of network articles (See Table 6). If we create a ratio of network articles per total articles in the DSBE research area, then the highest ranked built environment research areas are Collaboration, Building specifications, and People, communities and culture.

The DSBE research area of Management contains 107 articles, of which 11% are network articles. The SNA methods could be of great use there. Many of the articles concern coordination of actors in projects, teams, stakeholder networks, firms, and networks of actors over the lifecycle. The ties between actors contain e.g. technology, sustainability, business, finance, workflow or resources. All of these management factors can potentially be researched using SNA, and the SNA metrics used could be for instance network centrality, density, cohesion, bridging, and/or betweenness (Table 7).

The DSBE research area of Economics has 70 articles, of which 3% concern networks. The DSBE Economics is primarily quantitative and can potentially use SNA metrics to relate sustainable economic measurement to traditional econometric measures of cost, value, and socioeconomic progress. The economics areas where SNA can be of use are centrality and density measures because these have been used in other economics research.

The DSBE Building production research area has 270 articles, and 16 of those concern networks. The 16 network articles concern relationships between actors within building projects, and relationships with actors outside of the building project, such as planning authorities, agencies, and suppliers. More than two thirds of the 270 articles are empirical, and relationships between various actors is a key theme in that research, and relationships within and outside of building production are most often studied separately. A potential contribution that SNA can make is to provide an array of metrics that connect networks within and outside building production projects. Useful SNA metrics are e.g., layered networks and inbetweenness.

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Table 6. Number of articles on Digitalization in Sustainable Built Environment research that cover networks, and whether they use SNA, qualitative, quantitative, and conceptual research. A single article can contain several topics and methods.

DSBE topic areas	Sustainability articles	Network articles	SNA methods	Quantitative methods	Qualitative methods	Conceptual research
Management	107	12	1	48	40	38
Economics	70	2	0	35	19	26
Building production	270	16	1	115	113	87
Collaboration	12	3	0	2	3	8
AEC services	28	2	0	17	8	8
Procurement	18	1	0	7	3	9
Construction material and tools	173	2	0	62	66	66
Building specifications	6	1	0	2	1	3
Environment	282	14	0	108	115	105
Life-cycle	99	4	0	36	43	37
Building use	35	1	0	17	17	9
Construction disassembly	35	1	0	12	14	13
Material recovery	53	1	0	17	15	27
Building information	26	0	0	7	11	10
People, communities and culture	44	7	0	15	14	18
Building performance	53	5	0	24	19	19
Education	11	0	0	7	5	3
Governance, legislation and policy	104	5	0	30	33	48

The DSBE Collaboration research area has 12 articles out of which 3 concern networks. The research on collaboration focuses on collaboration within construction, such as integrated projects, and collaboration for specific purposes, such as green building certificate approval. Collaboration could benefit from SNA by that it can empirically help study collaborative relationships and collaborative networks, and the network dynamics. Potentially useful SNA metrics are network centrality, indegree, outdegree, and network layers.

The DSBE area of AEC services has 28 articles out of which 2 concern networks. The AEC research area covers how architects collaborate with other professional groups in projects, and how architect work collaboration is changed by use of new

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technology. Potential areas for contribution are how architects collaborate in networks at early phases, such as planning, and construction, and how networks change from one phase to another. Comparison of ties, actors, and networks in different phases can be useful, and time series analysis of architect network position over project evolution can also advance research.

The DSBE area of Procurement has 18 articles, of which 1 is on networks. Procurement can be analyzed in terms of ties between suppliers, and ties between suppliers and tenants or built environment facility managers. Network ties between suppliers that work on the same digital platforms can also be useful for the analysis of how supplier networks should be built in procurement.

The DSBE area of Construction materials and tools has 173 articles, of which 2 covers networks. Network properties of digitally connected materials and tools is an area in rapid growth, and the transmission of data across various platforms, sensors, tools, can be combined with digital monitoring of materials during construction and maintenance of the built structure. Network analysis can also be used for the analysis of how materials and systems interact with actor's decision making on sustainability. Useful SNA metrics are primarily those that connect different layers of network data, such as layered networks, but also how networks are composed with ties and actors.

Table 7. Key future research opportunities per DSBE research areas.

DSBE topic areas	Key future research opportunities: suggested SNA method and analysis	SNA metric that can be used
Management	SNA is very suitable for the study of teams, coordination, collaboration, and stakeholders.	Network centrality, density, bridging, betweenness, inbetweenness centrality.
Economics	Efficiency, complexity and performance related to network composition.	Network centrality and density.
Building production	Relationships between actors in production, and workflows between actors.	Network centrality, indegree, and outdegree.
Collaboration	Collaborative relationships and networks.	Network actors, ties, centrality, distance, cohesion.
AEC services	Architect collaborative networks change because of new technology, and planning and construction can be more integrated.	Comparison of network actors and ties at different phases, and time series network position measures, such as network centrality.
Procurement	Actor network constellations, and collaboration between suppliers.	Ties between suppliers, and between suppliers and tenants.
Construction material and tools	Digitally connected material and tools in construction and use and maintenance of the built structures. Relationship between materials and systems networks, and actor decision making on sustainability.	Ties, Actors, Network layers.

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Building specifications	Actors, systems, and specifications are tied to each other and can be studied by network studies.	Ties, actors, networks.
Environment	Actors' environment effect can be tied to each other in networks of different environmental effects.	Ties, actors, networks, indegree outdegree, network layers.
Life-cycle	Network evolution over time.	Change of ties, actors and network metrics using time series data.
Building use	Data on actors, ties, and networks of building technical data, occupant behavior data and business data.	Ties, Actors, networks, and network layers of technical and behavioral data.
Construction disassembly	Map network of actors and materials used as buildings are demolished or repurposed.	Ties, actors, networks.
Material recovery	Analysis of materials and actors that can use and recycle materials from demolished or repurposed construction.	Ties, actors, networks that can show which actors and materials are combined now, and which could be combined in the future.
Building information	Analysis of BIM models that include sustainability metrics.	Ties, actors, networks.
People, communities and culture	Interaction between the built environment and people, communities, and culture can be done using layered network analysis.	Network layers.
Building performance	Digital analysis of physical attributes of building networks and human tenant data on behavior, preferences and satisfaction is of great potential use.	Ties, actors, networks, inbetwenness, cohesion, network layers.
Education	Digitally distributed information can be analyzed for how easy it is to access, and how useful it is for users.	Ties, actors, networks, cohesion, propinquity.
Governance, legislation and policy	Digital work changes interactions between public and private actors, and SNA network analysis can help advance research on this.	Ties, actors, networks, closeness, network efficiency.

The DSBE area of Building specifications has 6 articles, of which 1 is on networks. Specifications on materials and construction processes are analyzed by life-cycle impact, and digital information makes it possible to study how networks of sustainable measurements interact, and to study the interaction between building specification regulators, suppliers, contractors, and owners. The relationship between materials, processes, and actors, for instance by the study of ties between actors in networks can be potentially useful to further the research in this domain.

The DSBE area of Environment has 282 articles, of which 14 concern networks. The Environment has many potential uses for network research, such as comparison of how different actors together have an effect on the environment, and how different measurements together reflect different

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dimensions of the environment. For instance, carbon dioxide emissions and biodiversity can be studied as two different layers of networks, and these can be compared to networks of actor groups, such as city planners, architects, contractors, and owners. The Environment can also be analyzed using large, environment wide networks, and subnetworks around and within buildings. Useful SNA measures are indegree and outdegree to determine flows in the network, and density, centrality, homogeneity, and inbetwenness of layers and subnetworks.

The DSBE area of Life-cycle has 99 articles, of which 4 are on networks. Life-cycle research has a distinct temporal component, and properties of materials are studied for their sustainability in 'stocks' of several buildings, or in individual buildings. Choice of materials is also related to how actors understand sustainability of materials, and how regulation and agencies influence choice of materials. The SNA method can be useful for the study of networks of materials, networks of actors and regulation, and also how networks of materials and actors relate to each other. Useful network metrics are ties, actors, and network metrics that can be used in time series data analysis. There are also powerful visual network evolution tools for change of networks over life cycle.

The DSBE area of Building use has 35 articles, out of which 1 is on networks. Building use involves facility management, occupant behavior, the influence of sustainability metrics on sustainable building use, and it also involves sustainability impact of the building on its surroundings. Useful SNA metrics are ties, actors, centrality, and also layers of digital, human behavior, and business data, such as green classification schemes.

The DSBE area of Construction disassembly has 35 articles out of which 1 concerns networks. Construction disassembly concerns the coordination of multiple actors and materials, not only at the end of the lifecycle of a building, but also as the building is renovated. Recycling of concrete in combination with other materials is studied in several articles, and so is involvement of architects in sustainable materials choice. The SNA method can help in empirical study of how materials are combined, and how materials and actors influence each other in sustainable decision making. Useful metrics concern actors, ties, networks, indegree, outdegree and inbetweenness.

The DSBE area of Materials recovery has 53 articles out of which 1 concerns networks. Materials recovery concerns not only the end of a construction's lifecycle, but also as the construction is re-purposed. There are technological advances in digital detection and classification of materials, and for digital models for demolition and recycling or reuse of materials. Relationships between actors, such as architects, developers, planners, agencies, contractors, and recycling firms need to be improved for materials recovery to function well. Useful SNA components and metrics include actor ties, and materials ties in networks that can be studied separately or in interaction with each other using SNA metrics, such as ties, actors, networks, betweenness, indegree and outdegree.

The DSBE area of Building information has 26 articles, but none of them concern networks. Most of the 26 articles describe the potential benefits of Building information models to DSBE actors, such as planners, architects, developers and contractors, and the articles also point to how BIM can be used to improve the collaborative ties between those actors. The articles also point

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to the large amounts of digital data available, and suggest that data can be used for research. This points to the fact that SNA can be used to analyze data, in particular regarding the collaborative relationships between actors in the DSBE sector. In particular, SNA could be used to expand the scope of metrics in object data in BIM models, so that objects would also include sustainability data. Another useful research direction would be to study how network collaboration affects sustainability. Applicable SNA metric is that of actors, ties and networks.

The DSBE area of People, communities, and culture has 44 articles, and 7 of them cover networks. The human/social dimension can be compared to construction dimensions in layered networks. For instance, social inclusion, noise, criminality, purchasing power, buyer/tenant preferences, and sustainability preferences can be overlapped with physical structures to analyze the interaction between the built environment and people, communities, and culture. Layered networks and inbetweenness analysis are the primary SNA metrics for such analysis.

The DSBE area of Building performance has 53 articles, of which 5 concerns networks. Many of the 53 articles concern evaluation of energy and materials sustainability performance, and some articles concern development of new systems for energy and materials. Most articles concern design and construction, and some concern existing buildings. Digital information of construction and buildings is dispersed in digital networks of sensors and cloud services, and the digital network can be compared and combined with construction site data. In existing buildings, sensor and cloud service data can also be compared with building user data, preferences, and satisfaction. Both in construction and in buildings, combinations of construction/building sustainability properties and actor network properties by such SNA metrics as inbetweenness, cohesion, network layers can help the research area of building performance advance.

The DSBE area of Education has 11 articles, but none on networks. Digital information on safety education and education of work schedules is growing rapidly in construction and facility management. Distribution and accessibility of information in a network can be analyzed by SNA metrics on actor use of information, and information on whether the information helped the user solve the problem. The SNA metrics of cohesion and propinquity can aid in the analysis of how effective network information use is.

The DSBE area of Governance, legislation, and policy has 104 articles, and 5 on networks. The planning and monitoring of construction is done by multiple public actors, who interact with multiple private actors, and the digitalization of the work of these actors transforms the way they interact. Much research concerns international comparison of standards, regulation, practice, and agencies. This research area could potentially be helped by SNA analysis of how ties and networks change because of increased digitalization, for instance on how relationships with agencies change for private actors in the built environment, and SNA can also point to how work could be improved by more close network connections.

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SUMMARY AND CONCLUSIONS FOR ENGINEERING PROJECT ORGANIZATION

This article set out to analyze how SNA can contribute to research that is focused on digitalization and sustainability in built environment context. A review of literature on Digitalization in Sustainable Built Environment revealed that only 1 article out of 506 used SNA. Since there is so little use of SNA, the potential for greater use of SNA seems high.

We took two steps in order to get a better grasp of the potential for contribution of SNA to the Digitalization in Sustainable Built Environment research. The first step was to analyze the broader literature of Digitalization in Built Environment research, where we found 23 SNA articles. We studied how SNA is applied and its contribution to research. An overall conclusion is that SNA is used to further empirical measurement of network relationships, and that it is often used in combination with other research methods. Another conclusion is that SNAs elaborate and precise measurement of networks, ties, and actors allows for more precise study of relationships between factors, and in that way, the SNA method is helpful in theoretical development. An example is that SNA provides precise measurement of construction project collaborative network relationships, which advances theory on how architects utilize more sustainable materials in the design of a building (Schröpfer et al. 2017).

The second step is to include the word 'network' in a review of the literature, because SNA is particularly well suited to networks. The search of articles on networks provided support for that SNA has a great potential for increased use, because there are 47 network articles out of 506 articles, but only one SNA article. Network research can be summarized in that it researches networks of actors or individuals on the one hand, or networks of physical objects, material, or data on the other hand. However, there is very little research that combines the actor/individuals level with the physical/material/data level. This provides a fantastic opportunity for future research, because SNA has a rich array of concepts and measurements that study ties between networks, and layers of networks.

The specific area of Engineering project organization identifies five 'grand challenges', and these are: 'the new project manager', 'project networks', 'innovation and growth strategies', 'systems integration', and 'lifecycle value and governance' (Sakhrani et al. 2017). The last of these four grand challenges are across firms, networks, or systems, and SNA is a method that is particularly suited to such studies, and 'actors' can be conceptualized as individuals, or collective actors, such as project teams, companies or agencies. To give an example, a prominent feature of the work of 'the new project manager' is to span boundaries in multiple ways, such as internationally, across units within organization, across organizations, and SNA can be a powerful tool for studying this empirically. The grand challenge of 'project networks' can be addressed by the study of networks of contracts in relationship to hierarchy, which can be done for instance by conceptualizing contracts as actors. Project networks can also be studied by comparing networks, virtual networks, and hierarchies using SNA. The grand challenge of innovation and growth strategies can be addressed by the study of how global project opportunities and uncertainty can be managed in knowledge networks and agile collaboration through

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SNA method. The grand challenge of systems integration can be addressed by multilevel network analysis, and dynamic system analysis using SNA. The grand challenge of lifecycle value and governance can be addressed empirically by SNA because it can tie actors and resources together over the lifecycle. The grand challenges are all systemic, and SNA is one of the most rapidly growing systems-level analytical tools, and so we find that it can add to engineering project organization research. More widely, global sustainability challenges require scientific breakthroughs, and research in the built environment sector is important because that sector has a large effect on sustainability. For instance, construction, buildings and transportation are major CO2 emitting industries, and they are all integral to the built environment. Methodological advances done in this article is a step towards addressing the global sustainability challenges.

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Appendix 1. Methods, theories and future research areas in the 23 SNA articles.

Author(s)	Year	Methods used	Theories / key concepts	Future research avenues proposed in the articles
Pryke and Pearson	2006	SNA and Qualitative	Incentives in project governance	Further case studies on financial incentives within construction project coalitions
Boutilier and Zdziarski	2017	SNA	Stakeholder network management and social licence	Integration of sustainable development goals into construction projects by paying attention to the social network structures
Keung and Shen	2917	SNA and Quantitative	Competitiveness, interfirm networks, network strategies	Project networks approach to competitiveness and collaboration
Loosemore	1995	SNA and Qualitative	Organizational system for reacting to problems occurring during construction projects	Linking structural characteristics and behavior with problem-solving effectiveness
Larsen	2011	SNA, Qualitative and Quantitative	Innovation diffusion	Research on attributes which contribute to the innovation diffusion process, such as needs, actor thresholds, selective exposure, power, groupthink, peer pressure and contextual thresholds
Park and Lee	2017	SNA and Qualitative	BIM, coordination	Research on productivity in the AECO industry
Priven and Sacks	2015	SNA and Qualitative	Production management, Project and Organization / People (p. 2)	Coordination of workflows in construction projects
Schröpfer et al.	2017	SNA, Qualitative and Quantitative	Knowledge transfer (KT) practices in construction projects	Knowledge networks and knowledge flow maps in relation to the performance of the built outcome
Teo and Loosemore	2014	SNA and Qualitative	The roles of protest group members	-
Teo and Loosemore	2017	SNA and Qualitative	Stakeholder theory, social capital and community protest	Use of role theory to understand protest identity

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			in project management	and behavior in construction protests
Thorpe and Mead	2001	SNA and Qualitative	Communication, construction projects	Further research on technology-supported project communication
Li et al.	2016	SNA, Qualitative and Quantitative	Prefabrication housing production	Framework for risk mitigation actions and analysis of stakeholder participation in prefabrication housing production projects
Solis et al.	2013	SNA, Qualitative and Quantitative	High performance teams in construction projects	Further use of SNA metrics to study team performance in construction context
Zhang et al.	2013	SNA, Qualitative and Quantitative	Team flexibility and sharing tacit knowledge	Tacit knowledge sharing and team flexibility in construction engineering and management field
Lee et al.	2016	SNA and Quantitative	Topological competitiveness based on social relationships between firms	Use of topological characteristics of social relationships, and other SNA measures, to identify firm's competitive positions
Dogan et al.	2015	SNA and Qualitative	Coordination in Construction	Management of shared resources, constraints, relationships and dependencies, as well as relation between centrality index and managerial performance
Cao et al.	2017	SNA and Quantitative	Dynamic network perspective on collaboration in the construction industry	Dynamics of collaborative networks for BIM implementation and variation of BIM implementation practices
Zhou and Irizarry	2016	SNA, Qualitative and Quantitative	Subway construction accidents	Further research on causal factors and dynamic network structure and behaviour in construction accidents
Pishdad-Bozorgi et al.	2017	SNA and Quantitative	Relationships and interdependencies between essential practices in flash-track projects	Exploration of semantic network analysis in construction management research

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Lin and Tan	2014	SNA	Performance in public sector organizations	Use of efficiency analysis and network analysis to study management issues.
Cao et al.	2018	SNA	Collaboration networks and organizational competitiveness.	Further studies on the mechanisms of how project-based relationship networks affect performance of design and construction organizations
Wambeke et al.	2014	SNA	Task variation in construction projects	Use of SNA measures to identify and manage variation in construction projects
Papadonikolaki et al.	2015	SNA	Complexity in industry supply chain and BIM	Use of SNA based models for analyzing, supporting and improving BIM-enabled supply chains

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