A Holistic Framework for the Implementation of Big Data throughout a Construction Project Lifecycle

Makram Bou Hatoum[a], Melanie Piskernik[b], and Hala Nassereddine[a]

[a]Department of Construction Management and Civil Engineering, University of Kentucky, USA
[b]Institute of Interdisciplinary Construction Process Management, Technical University of Vienna, Austria
E-mail: mbh.93@uky.edu, melanie.piskernik@tuwien.ac.at, hala.nassereddine@uky.edu

Abstract –

As the world witnesses the fourth industrial revolution, construction remains a newcomer that lags in its adoption of technological innovations. The information-intensive nature of the construction industry, coupled with its multidisciplinary nature, has pushed construction to enter the era of Big Data and has provided fertile ground for research on Big Data. Numerous efforts have been undertaken to investigate the use of Big Data and its impact on construction. This paper builds on the existing body of knowledge and explores the implementation of Big Data throughout the different phases of a construction project. By synthesizing the extant research corpus, this empirical study provides insights into the current state-of-adoption of Big Data throughout the lifecycle of a construction project, its sources, capabilities, and benefits. The findings of this paper are combined into a Big Data Framework that summarizes the "what, how, where, and why" of Big Data implementation in the construction industry.

Keywords –

Big Data; Adoption Framework; Construction Industry; Project Lifecycle; Benefits; Use-Cases.

1 Introduction and Background

Industries worldwide are currently in the midst of the fourth wave of technological advancement, known as Industry 4.0. This wave of advancement is a collection of various technologies that promote innovation in industries through the convergence of humans, technology, and information [1]. The construction industry is not an exception to the pervasive digital revolution. The industry deals with sheer volumes of data arising from different disciplines throughout the different phases of a project.

Despite the information-intensive nature of the construction industry, it remains slower than other industries in harnessing the power of data [2]. Researchers have identified various barriers that prevent construction from fully exploiting information and communication technologies (ICT) and harvesting construction data. Example of barriers include the highly fragmented nature of the industry, the temporary nature of projects, the uniqueness and complexity of construction projects, the inadequate coordination and collaboration between stakeholders, the lack of ICT knowledge and skills, the lack of standardization, the challenge to change organizational culture, and the unclear return on investments [3].

The above-mentioned barriers pose a multi-dimensional challenge that can be tackled from different aspects. One aspect that this paper explores is ICT. Research in the industry showed that data captured through ICT can be used to address crucial issues associated with cost, planning, risk management, safety, progress monitoring, and quality control [4]. This collected data is the major source of Big Data, which, compared to small data sets or sampling, can help to draw a fuller, more trustworthy picture in all areas of construction [4].

Big Data in construction can be defined by five different attributes: volume, variety velocity, value, and veracity (5V's). The interdisciplinary nature of the construction industry produces large, heterogeneous, and dynamic construction data, which mirrors the volume, variety, and velocity attributes of Big Data [5]. Moreover, primary sources of Big Data in construction generate data in large volumes, numerous formats – including images and AutoCAD and Revit enabled files, and in near real time [6]. As for value and veracity, these two attributes are conveyed through the ability to extract information from construction's Big Data and detect and analyze patterns and trends [7].

Primary sources of Big Data in construction include 1) people who are continuously generating and sharing information, 2) IT-enabled construction equipment that gather, share and store data, and 3) internal Information Technology (IT) systems such as Building Information Modeling (BIM), planning and procurement software [8].

The vast accumulation of data from these sources, especially from BIM, has been studied by numerous researchers. BIM serves as a starting platform to adopt Big Data approaches. [9] stated that Big Data is essential in "bridging BIM and building" (BBB), where technologies such as radio-frequency identification (RFID), cameras, Geographic Information System (GIS), global positioning system (GPS), and Augmented Reality (AR) capture real-time information from real-life physical project processes and synchronize it with BIM to track construction and generate as-built models. The authors developed a BBB conceptual framework that uses data beyond the construction phase of a project and generates architectures of real RFID-enabled BIM systems for prefabricated housing productions. In another study conducted by [10], BIM was extended to "dynamic BIM", an innovative approach which stores information from the early phases of the project through facility management, with a cloud-based system framework to effectively retrieve required information for various applications by Big Data analysis based on parallel processing of large data sets.

This integration of BIM and Big Data was classified by [11] as an example of a technological factor that drives Big Data adoption in the construction industry. Another example of a technological factor considered by the same study is the advantage of information derived from Big Data analysis such as decision making, planning, and simulations. The study also noted two other factors that drive the adoption of Big Data: organizational factors which reflect Big Data's ability to improve design and execution efficiencies and project management capabilities, and environmental factors which represent the availability of construction related technology that can collect, store, analyze and visualize Big Data [11] . Moreover, data that is being collected and stored by construction stakeholders can be analyzed to continuously assess and improve stakeholders' management maturity by generating new types of holistic and adaptive maturity models [12]. For example, social network analysis (SNA) and text mining techniques can be used to recognize patterns of communication within the organization and among project stakeholders, and evaluate the extent to which documents reflect project management processes [12].

In addition to the aforementioned drivers, Big Data presents new opportunities for construction firms to innovate and improve current construction processes [13]. Big data can empower project progress monitoring and optimize resources allocation by providing new ways to simplify the detection of performance deviations and give stakeholders more time for corrective actions on ongoing projects. This capability can be also extended to future projects by allowing stakeholders to build their knowledge to thoroughly understand the adopted practices [13].

To examine the status of Big Data research in construction, [6] performed an extensive study that analyzed Big Data research in construction and mapped out its orientation. The authors found that Big Data studies mostly focused on utilizing Big Data on construction projects to monitor progress and performance, enhance time and cost management, and inform better decisions. The authors also noted that other studies focused on site safety and worker safety behavior, energy management of buildings, decision-making framework design, and resource management and tracking during construction [6].

This paper builds on the existing body of knowledge and synthesizes previous research efforts into a framework that holistically summarizes the implementation of Big Data in the construction industry. To achieve the research objective, the study starts by first identifying applications of Big Data throughout the lifecycle of a construction project – from conceptual planning to demolition. Next, ten major benefits of adopting Big Data in the construction industry are extracted and discussed. Finally, a holistic framework that summarizes the "what, how, where, and why" of Big Data implementation in the construction industry is proposed.

2 Big Data Applications throughout the Construction Project Lifecycle

Numerous research efforts were reviewed and examined to extract potential applications of Big Data throughout the lifecycle of the construction project. The project phases used in this paper are those discussed by [14] who divided the project lifecycle into seven phases: concept planning, design, pre-construction, construction, commissioning, operation and maintenance, and demolition.

Throughout the review of the extant literature, the authors noted that some project phases were discussed interchangeably, namely conceptual planning and design, and construction and commissioning. Thus, this research grouped the seven phases into five stages, discussed below, to accommodate the Big Data literature.

2.1 Stage 1: Conceptual Planning & Design

A project lifecycle begins with conceptualizing the project and developing the design. During this stage, geospatial, a type of Big Data , can provide planners and designers with important information about the project location, infrastructure, public spaces and resources [8], [15]. [16] added that Big Data can also offer insights from previous projects about future residents, their behavior, and preferences, thus facilitating stakeholders' understanding of end-users' needs by and designing the project for optimization.

[17] discussed that Big Data can be integrated with BIM and online social networks to select sustainable energy solutions capable of optimizing the project performance. This can enhance project design and is particularly valuable for green buildings. Simulations can also be generated with Big Data to evaluate various design alternatives for space and efficiency, creating a new approach for producing innovative designs [16].

Another application of Big Data in the project early phases is found in the bidding process of traditional projects. Tender price evaluation is one of the central challenges that owners face during bidding. While owners collect project cost data from all bids, this information is generally not used after a bid is awarded. To take advantage of historic data, project cost data need to be stored in the cloud. Then, Big data algorithms can be designed and generated to mine the stored data and allow the evaluation of tender prices in real-time [18]. Stakeholders can also use Big Data to estimate their profit. [19] indicated that the company or industry benchmarks currently used to estimate profit are not accurate as they do not reflect project-specific variations. The authors argued that the architecture Big Data makes it possible to quickly examine large amounts of project data, identify underlying trends, and understand the dependence between profit margins and project attributes.

2.2 Stage 2: Pre-Construction Planning

The second stage is pre-construction planning, which includes planning the construction phase of the project. The effectiveness of this stage relies on the proper use of all available knowledge needed to develop an execution plan [20]. Big Data collected from similar historic projects can be analyzed and used to ensure the robustness of the project plan by reducing uncertainty and allowing more accurate forecasts, projections, and planning [20]. Pattern analysis, simulations, and trend analysis are three approaches that are frequently used to analyze data during pre-construction planning and aim to assess implications of current issues and decisions, detect early warnings and threats that can impact project performance, consider consequences of design assumptions, and simulate future scenarios [20].

Another application of Big Data in this stage focuses on predicting the behavior of stakeholders and analyzing the reliability of their commitments, their level of collaboration, and readiness to share knowledge [20].

Moreover, historic and new data collected during this stage can be used to simulate different construction activities and tasks, and thus, improving project performance. These simulations become very critical when automating activities or tasks, as the effect of automation on safety, productivity, and parallel-occurring tasks need to be carefully analyzed [13].

2.3 Stage 3: Construction & Commissioning

The third stage discussed in this paper includes the construction and commissioning phases of a project. Most Big Data applications in this stage are used in capturing real time or near-real time data to track project progress and create as-built 3D models [9]. [21] reviewed different applications that use computer visual techniques for monitoring and analyzing activities performed on construction sites. These visual techniques are found to have the ability to analyze static images, time lapse photos and visual streams. [22] proposed an application that uses 4D plan BIM and 3D as-built point clouds models to track construction progress. The point clouds were generated from site photologs using structure-from-motion techniques.

Real time data can also be gathered using as built-in smartphone sensors to collect equipment-related data. The status of an equipment, i.e. off, idle, or busy, and the type of work performed, i.e. dumping or scoping, can be analyzed to assist construction personnel to better utilize the equipment, inform better decisions, and ultimately, have better control of the project [23]. Moreover, [24] indicated that setting laser scanners and video cameras on blind spots across the construction site allows the collection of new data that can be beneficial to equipment operators, by providing them with 3D workspace data, automatic object recognition, and rapid 3D surface modeling in near real time.

In addition to sensors, applications of IT are also being embedded into construction machinery. An example of such applications include machine-to-machine (M2M) [25]. M2M can be used on construction machines to recommend overhauls for construction end users on site at the optimum timing. This data can also help manufacturers better understand and transform their business models, thus creating enhanced machinery.

[26] explored a Big Data application for real time construction quality monitoring application to provide timely collection and analysis of data from ongoing activities. The application is a real time construction quality monitoring method for storehouse surfaces of reinforced cement concrete (RCC) damps using GPS, global navigation satellite business techniques, sensor technology, and network transmission technology.

[27] proposed an enterprise integrated data platform (EIDP) to overcome challenges such as poor interoperability of data and inaccurate manual entries between the business management and the project management, showcasing the value of Big Data for construction companies.

Applications of Big Data have been also explored for earthwork processes. [28] combined photogrammetry and video analysis for measuring the exact machinery productivity and determine site-specific performance factors. Photogrammetry was used to determine the volume of excavated soil, while video analysis was used to generate statistics such as loading and idle times.

Big data can also be used for human resources and labor. For example, [29] used Big Data to analyze worker behaviors in a metro construction in China. The study formed a behavioral risk knowledge base by combining vital unsafe behavior in multiple dimensions with the work breakdown structure of the construction. Then, the knowledge base, with the assistance of mobile applications and surveillance cameras, was used to detect unsafe behavior, analyze the factors affecting this behavior by Job Hazard Analysis (JHA), and match it with the predefined unsafe behaviors using Vector Space Model (VSM). All this information was also stored in a Big Data cloud platform and sorted by a Hadoop Distributed File System (HDFS).

2.4 Stage 4: Operation & Maintenance

The fourth stage includes the operation and maintenance phase of a project lifecycle. With properly installed technologies like RFIDs and sensors, facility managers can obtain the exact location and details of different building components to simplify monitoring, inspection and maintenance [9]. Beyond that, using BIM models and Internet of Things (IoT), Big Data can be generated for buildings to provide geometric and semantic information as well as state of building elements, all of which can be used to represent buildings within a virtual GIS environment for city monitoring and management applications [30].

Big Data that includes building information, in particular energy efficiency, has become one of the main concerns for a sustainable society. Despite the existence of current challenges – like analyzing accumulated data in a short time – Big Data analysis can be the solution for understanding energy consumption behavior and improving energy efficiency in the construction sector [31]. A successful example includes the analysis of energy consumption, environmental measures, and occupancy information using Big Data Analytics techniques to study building performance and visualize it on a building performance comparison application [32], [33]. This application was designed to handle large volumes of data with a user interface platform to change the options of the desired analysis. [34] reviewed sustainable construction management strategies that use quantitative Big Data approaches to monitor, diagnose, and retrofit the dynamic energy performance of buildings in use.

2.5 Stage 5: Demolition

The last stage of a project is demolition. Big Data gathered from construction waste management indicators, especially in the demolition of a project, can assist in managing the disposal of the deconstructed materials and reduce the waste generation of the contractor [4]. Examples of performance indicators include waste generation rates, costs associated with waste collection, storage, transportation and recycling, and revenues and savings from selling waste [35]. This data can also be beneficial for the public, where the government can use Big Data to manage construction wastes, and monitor air and noise pollution from construction activity [36].

3 Benefits of Big Data

Big data has a wide range of applications throughout the project lifecycle, as highlighted in the previous section. Various research efforts have also discussed the benefits that Big Data can offer to the construction industry. These potential benefits are discussed below and are summarized in Table 1:

- Enable data driven simulations and solutions for different on-site construction activities to optimize construction site layout and resource allocation [16], [17], [37]
- Enable the delivery of the right information such as project location, surrounding environment including traffic and parks, and infrastructure overview [15], [18]
- Enable the monitoring and assessment of various facility performance areas, specifically energy, and thus empowering facility managers to perform their work more efficiently [7], [30], [32]–[34], [38], [39]
- Enhance decision-making by accessing and analyzing previously collected data and identifying trends and patterns [3], [4], [7], [37]
- Enhance the flow of information between project stakeholders and across project phases. For example, this can be achieved with the applications that track real time or near-real time construction status and update as-built models for downstream players [7], [12], [37], [40]
- Facilitate collaboration and communication between stakeholders, which is of great importance, especially at the early stages of the project to align stakeholders' interests. Increase collaboration and communication ensure that all stakeholders have a clear understanding of the scope of work and expected outcomes [17], [20], [25], [37], [41]
- Improve project control including the location and status of labor, equipment, material and tools [21], [23]–[25], [28], [29], [42]
- Improve the accuracy of forecasting and promote better predictability, specifically during pre-construction planning where construction tasks can be simulated before execution to identify and remove barriers and constraints [7], [13], [17]–[20],

[36], [37], [43]

- Optimize project environmental performance, particularly waste management, during construction and demolition [4], [36], [44]
- Support electronic information management systems to centralize information throughout the project lifecycle [41], [45]

Table 1. Benefits of utilizing Big Data in Construction

Code	Benefits
B1	Enable data-driven simulations
B2	Enable the delivery of the right information
B3	Enable the monitoring and assessment of facility performance
B4	Enhance decision-making
B5	Enhance information flow
B6	Facilitate collaboration and communication between stakeholders
B7	Improve project control
B8	Improve the accuracy of forecasting and predictability
B9	Optimize environmental performance
B10	Support electronic information management systems

4 Big Data Framework

The culminating effort of this research is a holistic framework that provides an overview of the implementation of Big Data in the construction industry. Such technology frameworks can guide the adoption of technology in different construction firms and companies, develop implementation roadmaps, and revolutionize the construction industry to warrant project success [46]–[49]. The framework, illustrated in Figure 2, consists of four layers. At the core, the 5V's are outlined, representing the prerequisites of *what* is considered Big Data. The second layer discusses *how* Big Data is enabled. Data needs to be first properly collected from multiple sources including sensors, surveillance cameras, Radio-Frequency Identification (RFID) tags, laser scanners, Geographic Information Systems (GIS), operating documents, Global Positioning Systems (GPS), and BIM models, to name a few. Data can be collected throughout the project lifecycle when designing, planning, performing risk analysis, forecasting, among other activities. Next, Big Data engineering transpires where the captured data is processed and stored for current and future usage. Then, collected data is harnessed using different analytics forms such as data mining, statistics, and machine learning [5]. The third layer of the holist framework illustrates *where* Big Data is used and encompasses the seven phases of the project lifecycle introduced earlier in the paper. The size and color of the circles representing the phases is proportional to the frequent mention of the phase in the literature review. It can be shown from Figure 2 that Big Data applications in Construction, Commissioning, and Operation and Maintenance (i.e. stages 3 and 4) are frequently explored in the current body of knowledge. Finally, the fourth layer of the framework captures the reasons *why* Big Data should be implemented in construction and presents the 10 benefits identified in this study.

To illustrate how the framework can be utilized, a case study conducted by [9] about the use of Big Data to produce prefabricated housing is discussed. During the design stage, teams use BIM to completely design the project and extract the components that should be constructed and purchased. The BIM model can also show locations of auto-ID technologies to turn components into Smart Construction Objects that can communicate with each other and the end users. Another technology that was frequently used is RFID models and tags. RFID tags can carry information about the production of the prefabricated components and their status (such as: manufacturing, in-storage, delivery or received). Production of the prefabricated components can work in parallel with the "as-planned" schedule and the updated BIM model. Once the components reach the construction site, they are assembled and installed which is also reflected in the BIM model allowing the project team to track the progress of the work and develop the as-built model. This model will be transferred to both the commissioning and operation and maintenance stage, or facility management, which can help them easily identify one component form the other, monitor their performance, and simplify repair work. This data is also useful during the final stage, demolition, where the RFID tags used earlier in the project can show the location, design, and status of every component, allowing stakeholders to better plan for demolition and manage the generated waste. The use of Big Data throughout the different phases of the project leads to all the ten benefits discussed in Table 1.

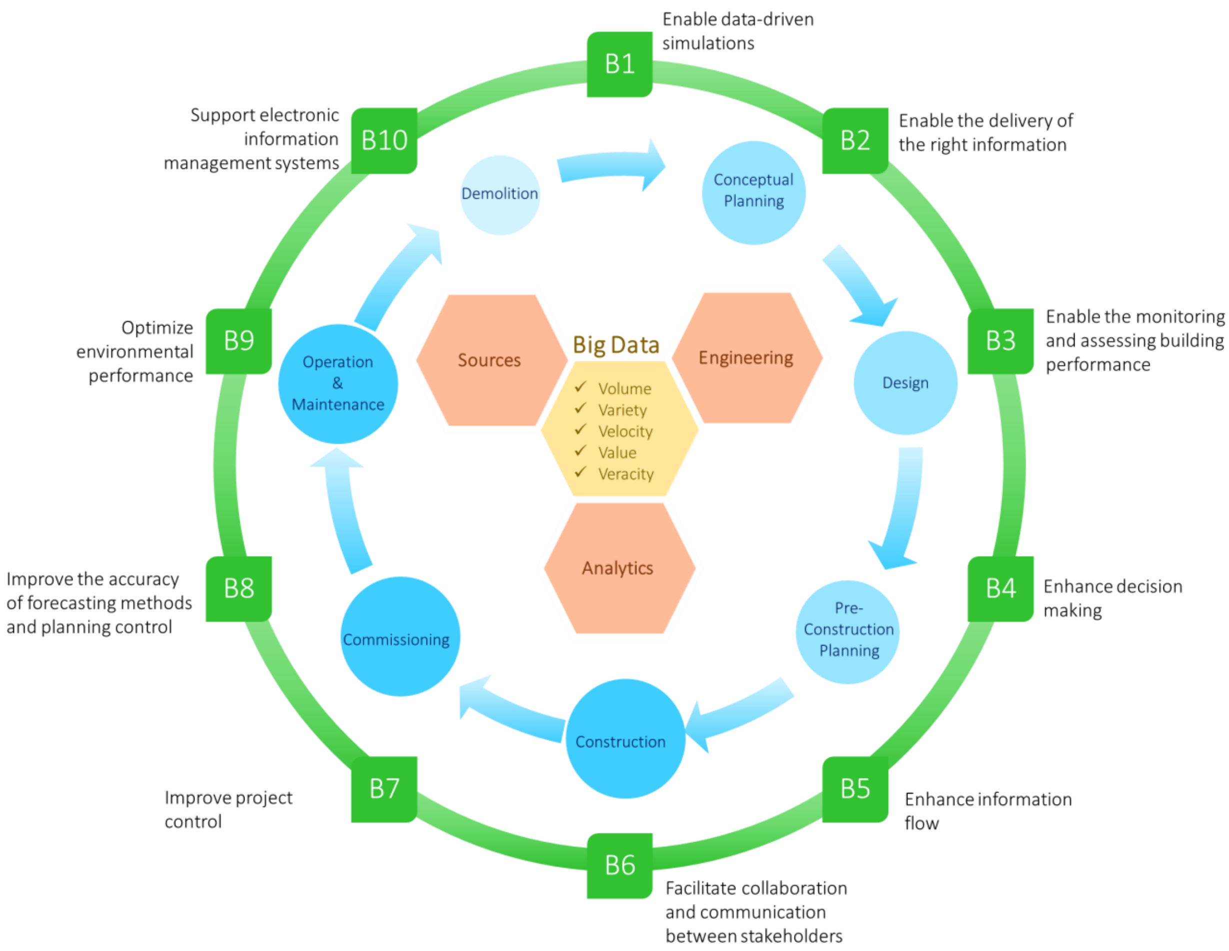

Figure 1. Big Data Holistic Framework

5 Conclusions, Limitations and Further Studies

The adoption of Big Data is integral to the construction industry. This paper performed a thorough and comprehensive review of Big Data adoption in construction. This review was summarized in a framework that shows the "what, how, where, and why" of the Big Data implementation in the construction industry. As revealed in the framework, the existing research corpus shows that the proper adoption of Big Data is possible throughout the entire lifecycle of a construction project. By using the right sources to gather Big Data, the proper engineering practices to process and store this data, and the appropriate analytics to explore it, the construction industry can achieve major benefits.

The proper implementation can revolutionize the industry, promoting high-fidelity collaboration among construction players, enabling stakeholder-driven analysis, enhancing decision-making, increasing transparency and information exchange, and enhancing project performance. Moreover, the framework of this study reveals that most studies targeted the construction, commissioning, operation and maintenance phases of the construction project.

The findings of this framework are limited by the research body reviewed in this paper. Further interviews with subject matters experts can be pursued to explore new applications, challenges, and benefits of Big Data adoption that the existing literature has not yet covered. Further research efforts can also explore more Big Data use-cases and applications in the less-discussed project phases such as demolition. More research can also focus on connecting these Big Data applications across the project phases to enable the industry's biggest potential.

References

[1] Sawhney A, Riley M., and Irizarry J. *Construction 4.0: an innovation platform for the built environment*. Routledge, New York, 2020.

[2] Nassereddine, H., Veeramani, D., and Hanna, A.

Augmented reality-enabled production strategy process. In *ISARC. Proceedings of the 36th International Symposium on Automation and Robotics in Construction*, pages 297-305, Banff, Canada, 2019.
[3] Martínez-Rojas M., Marín N. The role of information technologies to address data handling in construction project management. *Journal of Computing in. Civil Engineering*, 30(4):04015064, 2016.
[4] Lu W., Webster C., Peng Y., Chen X. and Chen K. Big Data in construction waste management: prospects and challenges. *Detritus*, 4:129-139, 2018.
[5] Bilal M., Oyedele L.O., Qadir J., Munir K., Ajayi S.O., Akinade O.O., Owolabi H.A., Alaka H.A., and Pasha M. Big Data in the construction industry: A review of present status, opportunities, and future trends. *Advanced Engineering Informatics*, 30(3):500–521, 2016.
[6] Ismail S.A., Bandi S., and Maaz Z.N. An Appraisal into the Potential Application of Big Data in the Construction Industry. *International Journal of Built Environment and Safety*, 5(2), 2018.
[7] Ekambaram A., Sørensen, A. Ø., Bull-Berg H., and Olsson N. The role of Big Data and knowledge management in improving projects and project-based organizations. *Procedia Computer Science*, 138:851–858, 2018.
[8] Sørensen, A. Ø., Olsson N., and Landmark A.D. Big Data in Construction Management Research. *SINTEF*, 3:405-416, 2016.
[9] Chen K., Lu W., Peng Y., Rowlinson S., and Huang G.Q. Bridging BIM and building: From a literature review to an integrated conceptual framework. *International Journal of Project Management*, 33(6):1405–1416, 2015.
[10] Chen H.M. and Chang K.C. A Cloud-based System Framework for Storage and Analysis on Big Data of Massive BIMs. *In ISARC. Proceedings of the 32nd International Symposium on Automation and Robotics in Construction*, pages 1-8, Oulu, Finland, 2015.
[11] Ram J., Afridi N.K., and Khan K.A. Adoption of Big Data analytics in construction: development of a conceptual model. *Built Environment Project and Asset Management*, 9(4):564-579, 2019.
[12] Williams N., Ferdinand N.P., and Croft R. Project management maturity in the age of Big Data. *International Journal of Managing Projects in Business*, 7(2):311–317, 2014.
[13] Skibniewski, M. and Golparvar-Fard, M. Toward a science of autonomy for physical systems: Construction. *arXiv preprint arXiv*: 1604.03563, 2016.
[14] Nassereddine, H. *Design, Development and Validation of an Augmented Reality-Enabled Production Strategy Process for the Construction Industry*. The University of Wisconsin-Madison, 2019.
[15] Lee J.G. and Kang M. Geospatial Big Data: Challenges and Opportunities. *Big Data Research*, 2(2): 74–81, 2015.
[16] Loyola M. Big data in building design: a review. *Journal of Information Technology in Construction* (ITcon), 23:259-284, 2018.
[17] Redmond A., El-Diraby T., and Papagelis M. Employing an Exploratory Research Stage to Evaluate Green Building Technologies for Sustainable Systems. *In Proceedings of the International Conference on Civil, Structural and Transportation Engineering*, paper 291, Ottowa, Canada, 2015.
[18] Zhang Y., Luo H., and He Y. A system for tender price evaluation of construction project based on Big Data. *Procedia Engineering*, 123:606-614, 2015.
[19] Bilal M., Oyedele L.O., Kusimo H.O., Owolabi H.A., Akanbi L.A., Ajayi A.O., Akinade O.O., Delgado J.M.D. Investigating profitability performance of construction projects using big data: A project analytics approach. *Journal of Building Engineering*, 26:100850, 2019.
[20] Caron F. Data management in project planning and control. *International Journal of Data Science*, 1(1):42-57, 2015.
[21] Yang J., Park M.W., Vela P. A., and Golparvar-Fard, M. Construction performance monitoring via still images, time-lapse photos, and video streams: Now, tomorrow, and the future. *Advanced Engineering Informatics*, 29(2):211-224, 2015.
[22] Han K.K., and Golparvar-Fard, M. Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs. *Automation in Construction*, 53:44–57, May 2015.
[23] Akhavian R. and Behzadan A.H. Construction equipment activity recognition for simulation input modeling using mobile sensors and machine learning classifiers. *Advanced Engineering Informatics*, 29(4):867–877, 2015.
[24] Wang C. and Cho Y.K. Smart scanning and near real-time 3D surface modelling of dynamic construction equipment from a point cloud. *Automation in Construction*, 49:239–249, 2015.
[25] Vanzulli, B. Kosaka, M. and Matsuda, F. Servitization in a construction machinery industry by using M2M and cloud computing systems. In *2014 11th International Conference on Service Systems and Service Management (ICSSSM)*, pages 1-6, Beijing, China, 2014.

[26] Liu Y., Zhong D., Cui, B., Zhong G., and Wei Y. Study on real-time construction quality monitoring of storehouse surfaces for RCC dams. *Automation in Construction*, 49:100-112, 2015.
[27] You Z. and Wu C. A framework for data-driven informatization of the construction company. *Advanced Engineering Informatics*, 39:269-277, 2019.
[28] Bügler M., Ogunmakin G., Teizer J., Vela P.A., and Borrmann A. A comprehensive methodology for vision-based progress and activity estimation of excavation processes for productivity assessment. In *Proceedings of the 21st International Workshop: Intelligent Computing in engineering (EG-ICE),* Cardifff, Wales, 2014.
[29] Guo H., Luo H., and Yong L. A Big Data-based workers behavior observation in China metro construction. *Procedia Engineering*, 123:190-197, 2015.
[30] Isikdag U. BIM and IoT: A Synopsis from GIS Perspective. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Science*, 40(2/W4):33-38, 2015.
[31] Koseleva N. and Ropaite, G. Big Data in building energy efficiency: Understanding of Big Data and main challenges. *Procedia Engineering*, 172:544-549, 2017.
[32] Ioannidis D., Fotiadou A., Krinidis S., Stavropoulos G., Tzovaras D., and Likothanassis S. Big Data and visual analytics for building performance comparison. *In IFIP International Conference on Artificial Intelligence Applications and Innovations*, pages 421-430, Springer, Cham, 2015.
[33] Ioannidis D., Tropios P., Krinidis S., Stavropoulos G., Tzovaras D., and Likothanasis S. Occupancy driven building performance assessment. *Journal of Innovation in Digital Ecosystems*, 3(2):57-69, 2016.
[34] Hong, T., Koo C., Kim J., Lee M., and Jeong K. A review on sustainable construction management strategies for monitoring, diagnosing, and retrofitting the building's dynamic energy performance: Focused on the operation and maintenance phase. *Applied Energy*, 155: 671-707, 2015.
[35] Yuan, H. Key indicators for assessing the effectiveness of waste management in construction projects. *Ecological Indicators*, 24:476-484, 2013.
[36] Chen X. and Lu W.S. Scenarios for applying Big Data in boosting construction: A review. *In Proceedings of the 21st International Symposium on Advancement of Construction Management and Real Estate*, pages 1299-1306, Springer, Singapore, 2018.
[37] Deutsch R. Leveraging data across the building lifecycle. *Procedia Engineering*, 118:260-267, 2015.
[38] Hashem I.A.T., Chang V., Anuar N.B., Adewole K., Yaqoob I., Gani A., Ahmed E. Chiroma H. The role of Big Data in smart city. *International Journal of Information Management*, 36(5):748-758, 2016.
[39] Ahmed V., Tezel A., Aziz Z., and Sibley M. The future of Big Data in facilities management: opportunities and challenges. *Facilities*, 35(13/14):725-745, 2017.
[40] Luboschik M., Berger P., and Staadt O. On spatial perception issues in augmented reality based immersive analytics. *In Proceedings of the 2016 ACM Companion on Interactive Surfaces and Spaces*, pages 47-53, 2016.
[41] Kähkönen K. and Rannisto J. Understanding fundamental and practical ingredients of construction project data management. *Construction Innovation*, 15(1):7-23, 2015.
[42] Teizer J. Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites. *Advanced Engineering Informatics*, 29(2):225-238, 2015.
[43] Safa M. and Hill L. Necessity of Big Data analysis in construction management. *Strategic Direction*, 35(1):3-5, 2019.
[44] Lu W., Chen X., Peng Y., and Shen L. Benchmarking construction waste management performance using Big Data. *Resources, Conservation and Recycling*, 105:49-58, 2015.
[45] Curry E., O'Donnell J., Corry E., Hasan S., Keane M., and O'Riain S. Linking building data in the cloud: Integrating cross-domain building data using linked data. *Advanced Engineering Informatics*, 27(2):206-219, 2013.
[46] Bou Hatoum, M. and Nassereddine, H. Developing a framework for the implementation of robotics in construction enterprises. In *EG-ICE 2020 Proceedings: Workshop on Intelligent Computing in Engineering*, pages 453–462, Berlin, Germany, 2020.
[47] El Jazzar, M., Piskernik, M. and Nassereddine, H. Digital twin in construction: an empirical analysis. In *EG-ICE 2020 Proceedings: Workshop on Intelligent Computing in Engineering*, pages 501–510, Berlin, Germany, 2020.
[48] El Jazzar, M., Piskernik, M. and Nassereddine, H. Transforming the AEC industry: a model-centric approach. In *Creative Construction e-Conference 2020*, pages 13–18, Budapest, 2020.
[49] Nassereddine, H., Schranz, C., Bou Hatoum, M., & Urban, H. A comprehensive map for integrating augmented reality during the construction phase. In *Creative Construction e-Conference 2020*, pages 56–64, Budapest, 2020.