Digitalization and Automation in Construction Project's Life-Cycle: A Review

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DIGITALIZATION AND AUTOMATION IN CONSTRUCTION PROJECT’S LIFE-CYCLE: A REVIEW

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SUMMARY: *The fourth construction industry revolution (i.e., Construction 4.0), driven by the fourth industrial revolution, introduces technological novelties to the construction industry in the direction of utilizing automation and digitalization potential. Various levels of maturity and adoption of these technologies have been identified separately in previous studies. In this study, a state-of-the art literature review is presented with the aim of determining the genesis and current levels of digitalization and automation, as well as their interoperability, among the main construction projects’ life-cycle phases. The results revealed that the construction project life-cycle phases are indeed at significantly different digitalization and automation levels. The initiation phase was found to be at a low level of digitalization and automation, the design and planning phase at a high level of digitalization with a low level of automation, and the execution phase at low-level digitalization with a higher level of automation. Since the topic is continuously developing, this research could be conducted in the near future to determine the advancements in comparison to the current conclusions.*

KEYWORDS: *digitalization, automation; drivers; Construction 4.0*

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1. INTRODUCTION

The construction industry is usually recognizable for its low productivity and reluctance to change, which are believed to be the main drawbacks that cause the lagging of the Architecture, Engineering and Construction (AEC) Industry behind the latest technological innovations adopted in other industries (Munoz-La Rivera et al., 2021). The traditionalism label, commonly connected to the AEC, is to a certain extent caused by the arising issues of the lack of skilled workers and the lack of funding required to modernize the equipment used on the construction site and in production (Chen et al., 2018; Cai et al., 2020; Delgado et al., 2019). Furthermore, the construction industry is considered to be highly segmented, meaning there is an insatiable need for workers, more efficient tools, and the risk of each construction project (CP) is high. Despite the fact that research in construction robotics and automation started in the 1980s, the construction industry was until recently one of the most unfamiliar fields for the robotics and automation community (Bock, 2007; Balaguer and Abderrahim, 2008). Therefore, an increasing number of efforts are emerging in terms of increasing the level of automation in all project life-cycle phases. The main reason for that may be the emergence of Industry 4.0 with its goal of increasing the productivity of the AEC by its automation through digitalization through adopting the current technologies i.e., Building Information Modeling (BIM), Internet of things (IoT), Big Data (BD), Additive Manufacturing (AM), Virtual reality (VR), Augmented reality (AR), etc. By implementing these innovations, the industry could benefit not only with an increased productivity level, but improved safety, quality, and project management, as well (Maskuriy et al., 2019). Ultimately, the emergence of numerically controlled electronic systems in the industry led to increased automation based on information technology (Karmakar & Delhi, 2021). However, various levels of maturity and adoption of these technologies have been identified globally and locally (i.e., among European Union Member States) and relatively (i.e., in the main life-cycle phases of a construction project) (ECSO, 2021). Additionally, perhaps the major benefit of these technologies is the premise that they could be applied through all phases of the construction process, as well as at any point in the building's life-cycle. According to a report presented in a study (Jacobsson and Linderoth, 2021), digitalization is the single largest change factor of our time, since the application of digital technologies is the key to change and increased efficiency in most areas of the construction industry, especially in three major life-cycle phases of construction projects, i.e., the design and engineering phase, construction phase, and operation phase (Aghimien et al., 2018). In relation to digitalization, automation can be defined as a self-regulating procedure by utilizing computerized machines to carry out various tasks and these machines can work accordingly with a program that regulated their behaviour (Oke et al., 2017). Furthermore, construction automation can be defined as a new set of technologies and processes that have the potential to change the entire course and idea of construction (Bock, 2015). While digitalization enables the digital support of a work, automation enables its independence. It is anticipated that by automating construction activities, the project's quality increases, and opportunities open for new materials and techniques (ECSO, 2021). In the early stages of digitalization and automation, technological constraints restricted efforts in their development to digital technology capabilities within and outside companies, which is still also often the case (Lundberg et al., 2021). Nowadays, the demands for construction projects are characterized by a short design and build period, increased quality, and low cost, which is where automation can be of immense impact (Bock, 2008). An autonomous construction system would be best suited for these kinds of demands since it could handle unpredictable conditions during the course of a project while operating without supervision or intervention (Melenbrink et al., 2020). Automation in construction processes can decrease the demand for a workforce, which is extremely useful in countries with a workforce shortage or with high labour costs. Also, the construction phase could be less weather-dependent throughout the entire year despite the unfavourable climatic conditions. Another noteworthy aspect is the everlasting and crucial industry problem of construction site work safety, which could be increased by production automation. The goal is for workers to spend less time operating at great heights, great depths, extreme temperatures, radiations, and approaching inaccessible terrains. Additionally, industry automation is believed to bring a decrease in construction waste due to the rationalization of resource consumption, decrease human errors, or at least the impact they have on the project. Ultimately, it is believed to help the construction sector build better, face fewer issues, increase productivity, decrease greenhouse gas emissions, etc. (ECSO, 2021). Despite the aforementioned benefits automation could bring to the construction industry, the level of its implementation is still found as low. This is because its full implementation faces many challenges, some of which are the construction companies and organizations of a specific region that provide the region with infrastructure at various levels—from design documentation to execution, as well as reconstruction and renovation of buildings (Tereshko et al., 2020). Also, some authors believe that one of the barriers to implementing automation in the construction industry is the different interpretations of the term construction automation (Chen et al., 2018). Designers consider automation as a way of automation of design and planning, contractors as automation of on-site tasks, etc. This also tends to be a challenging issue due to the different levels of automation and digitalization among the phases of a project. A high level of automation and digitalization of the design phase does not necessarily ensure the full benefit to the project's overall success if the construction phase has an extremely low or non-applied automation nor digitalization. However, the number of positive efforts and feedbacks of automation in all construction project’s lifecycle phases are continuously reported. This literature review is presented with the objective of determining the different levels of digitalization and automation in construction projects’ life-cycle phases and related innovations. For this purpose, more than 100 relevant references regarding innovations in digitalization and automation of projects’ life-cycle phases were analysed over a period of more than 50 years.

The remainder of this paper is organized as follows. In the second part, the applied research methodology was described. The third, fourth and fifth parts of the paper present the literature review of the levels of digitalization and automation in CP’s life-cycle where the third part of the paper concerns the digitalization and automation level in CP’s initiation. The fourth part deals with the digitalization and automation level in CP’s design and planning and the fifth part analyses digitalization and automation level in CP’s execution. In the sixth part, there is a discussion and in the seventh part, conclusions were made.

2. METHODOLOGY

This paper presents a focused, chronological literature review of digitalization and automation achievements in the construction project life-cycle phases. The main construction project life-cycle phases were divided into the initiating phase, the design and planning, and execution according to the standard definitions given by the Project Management Institute (PMI) and International Project Management Association (IPMA) (PMI, 2021; IPMA, 2021). The research was initialized by structuring the main keywords presented in Table 1 accordingly to the main construction project life-cycle phases, which provided a basis for the search of relevant papers.

TABLE 1: Research keywords, hypothesis and research questions.

The main construction project life-cycle phases		
Initiating	Design and planning	Execution
objectives, deliverables, team/stakeholders, studies	modelling, resource planning, scheduling,	construction technology, monitoring (efficiency, safety, quality)
Main keywords		
CP initiation, CP conceptualization, CP stakeholders	CP model, CP planning, CP resource planning, CP scheduling, BIM model	CP construction phase, CP execution, CP robotics, CP monitoring
Draft hypothesis		
DH1: low level of digitalization and automation	DH2: high level of digitalization with a low level of automation	DH3: low-level digitalization with a higher level of automation, with the most potential
Research questions		
RQ1: How is the initiating phase connected with BIM?	RQ2: Which are the current trends/directions of BIM development regarding the design and planning phase?	RQ3: Does the automation of construction execution enhance monitoring?
RQ4: What are the main challenges of digitalization and automation of a construction project’s life-cycle?		
RQ5: What are the main benefits digitalization and automation have brought to the construction project’s life-cycle?		
RQ6: How are the levels of digitalization and automation interconnected among construction project life-cycle phases?		

In order to define the research questions (i.e., RQ1 to RQ6), research draft hypotheses for each phase were structured based on initial studies and the authors' experience as well as the sequence of their ongoing research projects. The first three research questions focus on certain life-cycle phases, while research questions four, five, and six address the whole project phases. The literature review and the results presented in this paper are based on a total of 103 extracted references over the period of 1965-2021.

Table 1 also provided the basis for structuring the paper which was organized as the phases emerge throughout the project lifecycle. Each chapter presented the chronological appearance of the innovations regarding each phase of the lifecycle.

3. DIGITALIZATION AND AUTOMATION LEVEL IN CP'S INITIATION

Perhaps the first research on the impact of digitalization in the initiating phase of construction projects started in the late 1990s, where several authors have investigated the impact of information technology in construction projects (Back et al., 1996; Tan, 1996; Johnson and Clayton, 1998; Back and Moreau, 2000). An emphasis on automation was given in 2007 when authors in (Yang et al., 2007) conducted a survey to determine the impact of automation and technology on project stakeholder success. There were 209 completed projects analysed and the results of this pointed out that technology is critical to assist in the execution of project work functions and may contribute significantly to project performance in terms of stakeholder success. Also, it was found that even though a positive impact was noted in most projects, large projects achieve greater success in the case of automation implementation. In this perspective, in 2008, Bock (Bock, 2008) states that when contracting a project for automated building construction, the whole activity has to be furnished with robotic controls, planning, construction, and manufacturing of construction parts because the construction project should after signing the contract only represent a geometric configuration problem, timely organization problem and a physical implementation problem. In 2010, a study (Popov et al., 2010) presented the development of a project concept in a 5D environment by using a virtual building design and construction model. The main benefits of using BIM in project management/conceptualization were found to be the ability of BIM to manage graphical views and information, the collaborative environment and information sharing, the relationship of the building's model and its estimate, the possibility of economic evaluation at any project's stage, simulation of the construction process and the possibility to simulate the project's management. An interesting aspect presented in 2013 is the estimation of waste for construction projects which enabled an online platform that integrated data input models (material management, project management, Work Breakdown Structure (WBS) management) and online analytical modules (Li and Zhang, 2013). The system allowed analysis of the waste origin, waste stream, and work package where the results can be presented in graphical and non-graphical formats. Furthermore, it was successfully applied to a hypothetical construction project. Authors (Akintola et al., 2017) found in 2017 that BIM has also affected the project's stakeholders in a way that it developed new job roles for addressing the gap in industry knowledge of BIM. It was found that the new BIM roles will only exist while the core professionals' BIM knowledge is insufficient, and therefore should construction companies and project teams consider that when making decisions about staffing, role distribution, role definition, and team composition. Additionally, the lack of expert roles for specific fields and lack of project management on a higher level were emphasized. In this perspective, a paper in the same year reviewed the specialist role definitions in BIM guides and standards and found that they generally fall into two project roles and two organizational roles which are project BIM manager and BIM coordinator as project roles, and internal BIM manager and BIM modeller in the organizational roles (Davies et al., 2017). Also, as the BIM roles are evolving, it can be expected that the investors' demand and competencies will also change and metamorphose into an Investor 4.0. Another interesting paper (Onalaja et al., 2018) in 2018 proposed a system thinking framework for identifying uncertainties during infrastructure project initiation as a part of an ongoing thesis. The system implies the use of soft system analysis, i.e., the System diagramming technique for problem identification. In the same year, the authors (Joseph Garcia et al., 2018) proposed a framework that identified three key phases for BIM implementation. The first, i.e., initiation phase where a preliminary BIM adoption setup takes place via external and internal support with the creation of in-house BIM experts. The second one, i.e., the stabilization phase which implies the retention of in-house BIM experts via business practices with improving their skills and motivation, and the third, i.e., the progression phase which comprises scanning and exploiting external innovative BIM knowledge to sustain or gain a competitive advantage. In 2020, a paper (Santos et al., 2020) presented a BIM-based Environmental and Economic Life Cycle Assessment tool that aimed to improve the value of BIM models for automatic/semi-automatic simulations at early project stages. The main difference between this tool and the previous was the ability to import data from spreadsheets into the BIM model which resulted in *automatic Life Cycle Assessment (LCA) / Life Cycle Cost (LCC)* analysis. As for further development, the authors suggest adding domains to the tool since it only enabled adding information to architectural and structural elements. The main achievements in the initiation phase of the construction project lifecycle are chronologically shown in Fig. 1.

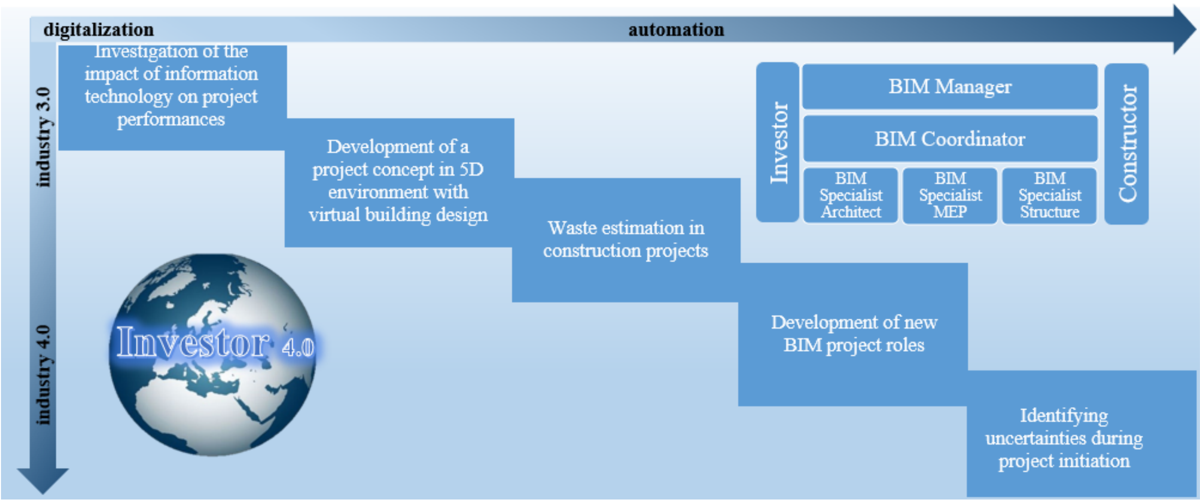

FIG. 1: Chronological milestones of digitalization and automation achievements in the initiation phase.

4. DIGITALIZATION AND AUTOMATION LEVEL IN CP'S DESIGN AND PLANNING

4.1 Digitalization and automation level in CP's design

Even though it might seem to current generations of engineers that the digital design, i.e., Computer-aided design (CAD), had no alternative previously and that its development was self-initiated and directed, it is not the case and the genesis of the digital design had its roots in traditional hand-executed designs where digitalization is a response to the problems that the traditional approach had. Early roots of the digitalization effort can be traced to 1965 when a system of computer programs was presented that could perform all routine work, usually done by an engineer regarding the design and selection of materials for the building while taking into consideration the geometric and load data (i.e., Massachusetts Institute of Technology (MIT) ″STRESS″ and the International Business Machines (IBM) ″FRAN″) (Bathurst, 1965). The following computer program for automated design was presented in 1972 and was intended for frameworks in steel tier buildings. Special emphasis was on the fact that it is not necessary to begin with good estimates, i.e., it is possible to begin the process with the input of any sizes for a geometry (Agaskar and Weaver Jr, 1972). Perhaps the biggest contribution to this field was introduced in 1974 when Charles Eastman proposed the first virtual model description of a building (Eastman et al., 1974), which nowadays is considered as the genesis of BIM. Following that, the Level of Detail (LOD) was first introduced in 1976 by James H. Clark where the guidelines proposed that objects farther away from the camera should be at a lower level of detail than those closer to the camera (Graham et al., 2019). Even though the design software emerged at this point, the designing standards were still connected and required a manual approach. But, in 1988, the development of software used for automated processing of design standards was presented where the check between the input and the design standards was done consistently by the automation of the design checking process (Cronembold and Law, 1988). In 1990, authors (Bédard and Gowri, 1990) stated that only well-structured and restricted tasks have been computerized. Therefore, the authors found that the knowledge-based expert systems (KBES) could be suitable for automating the design process of buildings, and in their paper (Bédard and Gowri, 1990), presented a prototype of such system. The mentioned prototype proposed a solution for the design process at the preliminary stage of designing by incorporating building code requirements, weather information, construction types, building materials, condensation check, and energy requirements into one KBES. Later, in 1994 a following knowledge-based system was introduced but intended for a detailed design of a prefabricated building. Whilst the architectural design is an input that is then adjusted to a modular grid, the location of structural supports is indicated, the floors and walls break down into elements that should be prefabricated and the output are detailed drawings of the prefabricated elements and the estimation of their cost (Retik and Warszawski, 1994). In the same year, a prototype based on a new graph-theoretical model for automated building design was presented. The system enabled residential buildings to be automatically designed and made it possible for the architect to concentrate on getting their preferences correct while the computer generates appropriate plans (Schwarz et al., 1994b; Schwarz et al., 1994b). Authors (Sacks and Warszawski, 1997) described an automated system for the generation of information regarding design and planning for multi-storey rectangular buildings, which includes object representation of the project, knowledge modules for information processing, and linkage to various databases. The system proposed a top-down approach for using multi-parametric templates that made the generation of full and feasible design solutions possible. A step further is The Building Design Advisor (BDA) presented in 1997, which is software supporting the integrated use of multiple analysis and visualization tools through the whole building design process (Papamichael et al., 1997). The system is based on a comprehensive design theory and used an object-oriented representation of the building while serving as a data manager and a process controller. What makes the system special is the fact that it automatically integrates several simulation tools like Schematic Graphic Editor (SGE) used for geometric characteristics, Default Value Selector (DVS) for the non-geometric parameters, etc. The automation of building code checking continued in 1997 when a proof-of-concept prototype that showed the feasibility of an online code-checking method was presented. The idea is for the client to send the design to a code-checker written in Java and the server checker sends back redlines after examining the data (Han et al., 1997). While the previous building project models supported computer-based integration between various construction applications, the author in (Sacks, 1997) proposed a project model for an Automated System designed specifically for including all the relevant information about the facility and the required resources. The model was tested for life-cycle application and validated on an existing 10 story building. The main limitation of the model is the fact that it is designed only for buildings with multiple floors of uniform, orthogonal shape. The authors stated that further research would focus on the implementation of a module for preliminary and detailed structural design, which will take the form of a collection of Intelligent Parametric Templates, including Work Assembly and Element methods, and associated databases. In 2000, Intelligent Parametric Templates (IPT) were presented in (Sacks et al., 2000) for structural design in an automated building system where the structural modules were developed using the IPT approach and later tested in the design of rectangular buildings. The authors mentioned two important limitations, i.e., the system only deals with rectangular-shaped buildings with uniform floor sizes and each basic IPT has to be programmed. Authors in (Nguyen and Oloufa, 2000) concentrated their research on information regarding spatial relationships between building components and described a computerized building design framework. The framework was developed by using geometric modelling techniques that helped to automatically generate and extract topological information of building components. The proposed system demonstrated the feasibility of using solid modelling techniques but is not able to satisfy all requirements from different AEC disciplines. As further directions, the authors list the extension of the deduction engine, completion of various deduction algorithms, and incorporation of a data exchange protocol. In 2005, the first computer-implemented automated building design and modelling and construction project cost estimating and scheduling system (DMES) was patented (Wakelam et al., 2005). The system provides a central source for all the design information in a two and three-dimensional spatial database which is accessible to all the members of a project team. The building model enables automated drawings, cost, scheduling information and even allows iterations of the model to determine the optimal design. In 2010, authors (Greenwood et al., 2010) investigated the lack of incorporating automated building regulations checking into the BIM model. Furthermore, they identified the main five requirements for automated code checking which are as follows: computer programmed check, rules have to be understandable, the lifecycle of the rule base has to be independent, development has to be compliant with open standards and consideration must be given to the industry processes. With energy efficiency and sustainable building design becoming imperative, paper (Kim et al., 2011) proposed the use of data mining techniques to develop an energy-efficient building design in order for the project members to improve future building designs by discovering important patterns in the previous designs. In 2016, in a study (Bres and Suter, 2016), it was concluded that the simulation of a building's energy performances has mostly been based on the geometric data of the building with the lack of HVAC (Heating, Ventilation, and Air Conditioning) system in that kind of automated simulations and proposed the translation of them from a BIM model. As for the further research directions, the authors propose more attention to the question of zoning and the appropriate resolution of automatically generated building models, as well as to quality control at different levels. With safety as a concern in the construction industry, authors in (Hongling et al., 2016) presented a Design for Safety (DfS) approach for the automated identification of potential safety issues or unsafe factors in construction by integrating BIM with

DfS rules. In 2017, a simple tool for the automated performance of seismic design of non-structural elements that is based on information extracted from BIM (Perrone and Filiatrault, 2017) was presented. Authors (Liu et al, 2018) proposed an automated BIM model approach intended for designing and planning to board light-frame residential buildings. They used a wood-framed residential building for the validation of the system and concluded that the approach rationalizes construction material waste. The development of automated building code checking continued in 2019 when a new framework that allowed a standardized method for design rules definition with the execution of International Organization for Standardization (ISO)-standard BIM was proposed (Ghannad et al., 2019). With the emergence of the Construction 4.0 paradigm, the possibilities of the integration of new technologies with BIM are being increasingly explored. Therefore, a study was conducted in 2020 to investigate the possibility of integrating BIM and Augmented Reality (AR) in the construction industry (Elshafey et al., 2020). It was found that software developers can consider the ease of use to create BIM-AR platforms that have a higher possibility to be used and accepted by the users. As the main limitations, the authors list that the sample size is small and the findings of this study cannot be completely generalized. In (Rizo-Maestre et al., 2020) a study was carried out in which traditional technologies were compared with integrated unmanned aerial vehicles (UAVs) and it was found that it improves accuracy, reduces errors, and saves time. In 2021, authors in a study (Suliyanti and Sari, 2021) explored the use of block chain platform throughout the building's life cycle. With the increasing issues regarding cybersecurity, this is a solution that enables information exchange in a secure manner. It can be concluded that by following the research in the field of construction informatics in the last decade, most of the innovation in the construction industry is focused on BIM (Klinc and Turk, 2019). Therefore, it is anticipated that BIM is in its metamorphosis and is becoming BIM 4.0 (Begić and Galić, 2021). The chronological overview of the achievements in the design phase of the construction project lifecycle is shown in Fig. 2.

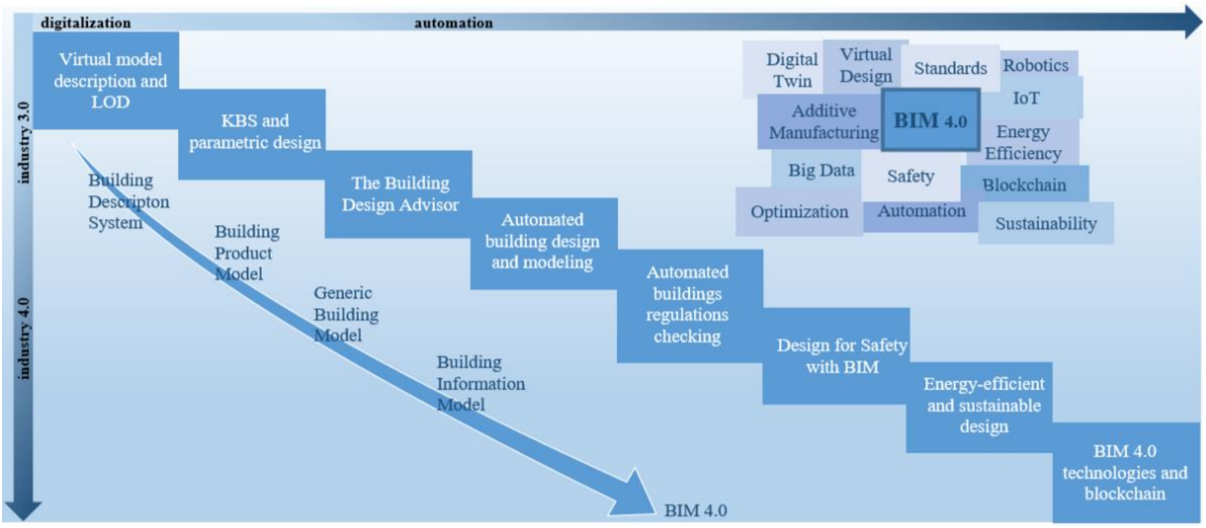

FIG. 2: Chronological milestones of digitalization and automation achievements in the scheduling phase.

4.2 Digitalization and automation level in CP's scheduling pre-execution

In comparison to the previous project life-cycle phase, the pioneer efforts of automating construction scheduling have only started just recently. In 2008, authors presented a case-based reasoning system for capturing, refining, and reusing project plans (CaBMA) (Xu and Muñoz-Avila, 2008). The system was made as a knowledge-based layer added onto a project management software, such as Microsoft Project, with the main aim to capture previous plans as cases and refine them to generate improved plans. In 2010, a scheduling system that applied a Multi-Dimensional (MD) CAD model, Object Sequencing Matrix (OSM), and genetic algorithms (Gas) was presented. The purpose of the system is to generate a schedule for the construction project which integrates information regarding time and cost. Since the system employs only MD CAD objects for information generation, it only considers the physical constraints between the construction elements but does not consider workspace, resources, and productivity (Feng et al., 2010). A similar system was presented in 2013 when authors (Chen et al., 2013) presented an automated and integrated scheduling and management system comprising of a 3D CAD Model, Database Linkage System, Intelligent Scheduling System, and a Dynamic Database System. The scheduling system covers all major elements of scheduling, such as distribution of labour, material, equipment, and space, scheduling, cost estimate, analysis of risks. For the verification, the authors developed a computer implementation called NDSM (N-Dimensional Project Scheduling and Management system) that proved to be efficient in determining whether the schedule is correct and which are the spatial implications and project constraints of elements. In the same year, FReMAS – a Functional Requirement Model for Automatic Sequencing was introduced. The purpose of the model is to create temporal constraints between the schedule elements from functional requirements. Also, it can automatically determine schedule variants by the constructions' requirements while trying to shorten the construction time (Chua et al., 2013). Authors (Kim et al., 2013c) proposed a framework by extracting spatial, geometric, quantity, relationship, and material information from BIM. The system is made to create tasks, calculate activity durations, and generate a schedule. First, it is necessary to prepare the BIM model to extract information from it by locating elements according to floors, extracting geometric and spatial information, assigning an element to a building area, and extracting material information. The following step concerns the information regarding element's quantity and material that is saved with its location and transformed into activity data which makes it possible to generate a schedule i.e., the activity list of data is exported to the format of an MS Project file and at last, if there is a need, the results are refined. As a limitation of this framework, the authors emphasized the potential issue of the time-consuming schedule generation in a case of a more complex BIM model. In 2014, a similar framework was proposed, where authors created a BIM model in Autodesk Revit, and generated a schedule through a Revit Application Programming Interface (API) (Liu et al., 2014). The schedule was also exported to MS Project, but in this paper, the emphasis was on the scheduling of panelised construction as the focus. The prototype was further developed by integrating resource constraints in 2015 (Liu et al., 2015). All of the aforementioned systems were referring to the schedule generation of one construction project. But, authors (El-Abbasy et al., 2016) presented an automated system for scheduling optimization of multiple construction projects called Multi-Objective Scheduling Optimization using Evolutionary algorithm (MOSCOPEA). The goal of the system is to obtain an optimal solution between different project's total duration, total cost, financing cost, profit, peak demand, and resource fluctuation. As the main limitation, the authors state that the model only considers finish-to-start precedence between activities and does not allocate a priority weight for each project. In 2019, a system for automated generation of schedules was presented, similar to the aforementioned ones, in the context of extracting data from BIM, but specific by creating work packages for schedule generation in reinforced concrete-framed buildings (Wang and Azar, 2019). The system was intended for the initial scheduling of concrete buildings with no curved or pre-stressed elements. As a limitation of the system the authors state that the scheduling of mechanical and electrical tasks has to be manually added to the schedule, and as further research directions they suggest scheduling the tasks for mechanical and electrical systems, effects of complex concrete elements, and automated resource and space calculation to optimize schedules. Another effort regarding work packages appeared in 2020 when authors presented a work package-based information model which captures all data that is required for a resource-constrained project scheduling problem (Wang et al., 2020).

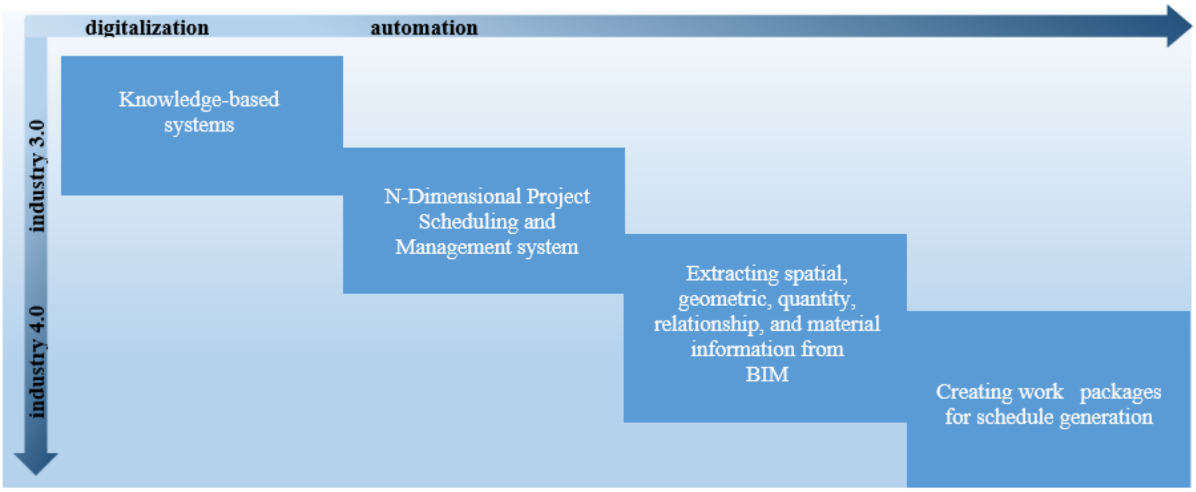

FIG. 3: Chronological milestones of digitalization and automation achievements in the pre-execution phase.

The research also proposes extensions and improvements such as extending the model to capture more data and introducing automatic progress tracking technology. As mentioned earlier, the automation of electrical and mechanical work was not yet introduced, until authors (Isaac and Shimanovich, 2021) presented a method for automated scheduling and control of mechanical and electrical works where a topological analysis of components location is used to define relationships between the activities and to determine the optimal schedule. In the same year, a simulation-based framework for automated planning of concrete construction works was introduced (Mohammadi et al., 2021). It was implemented in a case study where it successfully generated the construction processes, activities, and required resources based on the given constraints. The chronological overview of the achievements in the scheduling phase of the construction project lifecycle is shown in Fig. 3.

5. DIGITALIZATION AND AUTOMATION LEVEL IN CP'S EXECUTION

5.1 Digitalization and automation level in CP's construction

The level of automation in the construction phase is still mostly being researched and developed whereas the other project life-cycle phases have already shown significant efforts and applications in this perspective. According to paper (Gambao and Balaguer, 2002), research fields of automation in the construction phase are mainly based on two large groups, first, civil infrastructure such as automation of road, tunnel, bridge construction and second, automation of house building such as automation of skeleton erection, assembly, interior finish. According to Bock (Bock, 2007), the first construction robots had been designed at the beginning of the 1970s for prefabrication of modular homes in Japan and in the late 1970s planning started for the use of robots on construction sites. In the 1980s the first construction robots appeared on the construction sites and in the 1990s automated construction sites had been developed and implemented several times. Perhaps the most notable breakthrough regarding automation in road construction was the European Union (EU) Computer Integrated Road Construction (CIRC) Project, which provided the development of autonomous road pavers and asphalt compactors (Peyret et al., 2000). A similar example was the Open Systems for Road Information Support (OSYRIS) also based on autonomous guidance of machines based on Global Positioning System (GPS) and laser data (Balaguer and Abderrahim, 2008). As for the earthwork, an automated excavator was developed in the context of the University of Sidney project (Ha et al., 2000). Recently there is an increasing number of computer programs used for the infrastructure projects such as Civil 3D, Plateia, and Urban, which are believed to push the automation of this domain further. More significant and complex examples of automation in the construction phase of house building can be dated to the year 2000 when an automated system called Big Canopy for high-rise reinforced concrete buildings was developed with the purpose of reducing the overall project cost (Wakisaka et al., 2000). The system comprised a parallel material delivery system with automated overhead cranes and one construction lift under a climbing temporary roof frame. It was applied to a 26-story building, and it was found that it improves site conditions, shortens the construction period, decreases the amount of workforce needed, and reduces the amount of waste. It was also used in a case study conducted in the paper (van Gassel, 2005) where it was proven to reduce significantly costs, construction duration and improve working conditions. An interesting example was the use of Contour Crafting technology presented in 2004, which uses two trowels that act as solid surfaces and create smooth and accurate surfaces on fabricated objects (Khoshnevis, 2004) where the method has proven fast and effective with significant waste reduction. Also, the authors believe that contour crafting technology is a leading method for future extra-terrestrial constructions. Since steel beam assembly is considered a dangerous manual operation, an automated robotic beam assembly system was proposed by (Chu et al., 2009). Masonry works are considered as time-consuming manual operations in construction, so paper (Bruckmann et al., 2016) presented automated construction of masonry buildings by using cable-driven parallel robots. Because prefabrication is widely used in the construction industry, an interesting example is the automated re-prefabrication system where a robotic system was presented for the automatic disassembly of prefabricated construction and its reconstruction according to a new design (Kasperzyk et al., 2017). The system was validated on two small prefab constructions and proved successful according to the new chosen design and precision. Furthermore, single-task robots have been developed for performing construction tasks such as reinforcement production and positioning robots, automatic climbing formwork, on-site brickwork laying system, concrete distribution robots, concrete compaction systems, etc. (Bock and Linner, 2016). Most of them are still in the conceptualization phase and not capable yet of autonomous work where human control and interference are not required. The main achievements in the construction phase of the construction project lifecycle are chronologically shown in Fig. 4.

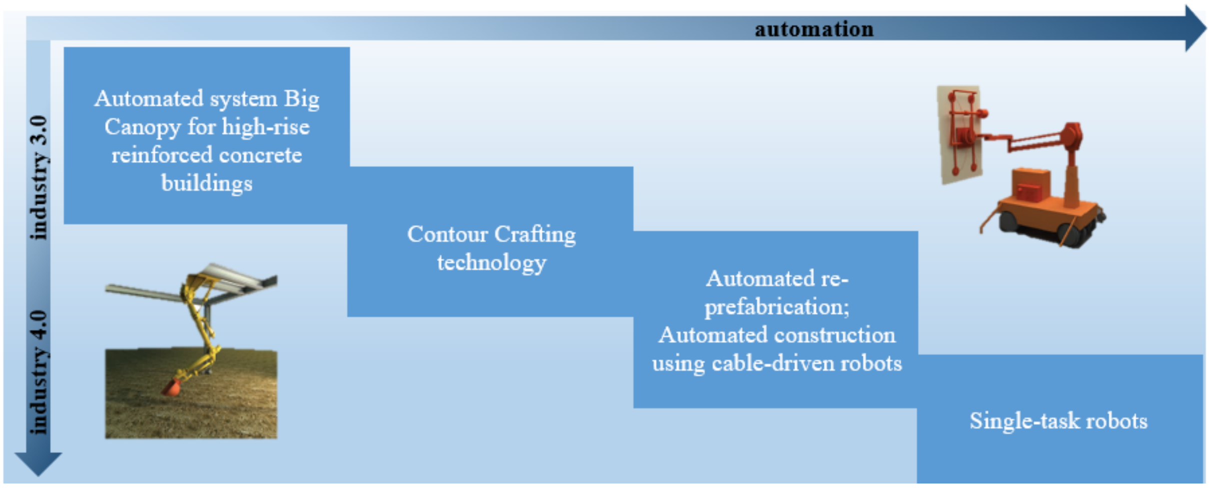

FIG. 4: Chronological milestones of digitalization and automation achievements in the construction phase.

5.2 Digitalization and automation level in CP's monitoring

One of the early but serious efforts of automation in construction monitoring can be dated back to 2000 and connected to a scheduling and progress control system Photo-net (Abeid and Arditi, 2003). It is an automated real-time monitoring system programmed in a Delphi environment that links time-lapse digital movies of construction activities and generates critical path method derived-bar charts. The time-lapse films that are taken by the cameras positioned on the construction site can be later used to compare the planned and performed schedule. The main limitations of the system are the use of a single camera with a limited frame rate and a need for manual input of activity progress. Authors (Dawood et al., 2002) conducted research on the automation of a communication system that would make the exchange of site information among the project member easier, where the results of the research showed a decrease of over 90 % in working hours that also generated an extreme reduction in overall costs. Furthermore, the system is estimated to provide a saving of over 98 % in time for the whole drawing register and distribution process. The following innovation was focused on the erection of prefabricated components of a building when a system named ArcSched, composed of a Geographic Information System (GIS) was unified with a database management system with the focus on integrating project's schedule and its design information that consequently increases schedule control efficiency and serves as real-time schedule monitoring (Cheng and Chen, 2002). Authors (Sacks et al., 2003) recognized that labour input of workers is an important factor that can be automatically measured regarding the project's performance. The idea was to measure the worker's locations by using automated data collection (ADC) and to integrate it with a building project model (BPM). The BPM has information regarding the geometry of the building, resources scheduled and allocated to certain activities. As for the further research directions, the authors recommend monitoring additional project indicators, integrating multiple monitoring sources using improved project data models, and developing expert interpretation systems. In 2003, PHOTO-NET II (Abeid et al., 2003) was developed as a sequel to the previously mentioned (Abeid and Arditi, 2003) where it introduced a new concept in time-lapse photography by enabling users to manipulate the frame rate and enabled the implementation of the technology in long-term construction projects on personal computers. In 2004, a Project Performance Monitoring System (PPMS) was presented that automates the monitoring process by using World Wide Web and database technology. The system includes eight categories of project performance measures: People, Cost, Time, Quality, Safety and Health, Environment, Client Satisfaction, and Communication (Cheung et al., 2004). Hence in 2006, an automated model was presented for identifying unsafe activities in a schedule (Navon and Kolton, 2006). The model can identify where the hazardous locations on the site are and give warnings, suggest protective measures and incorporate them into the project's schedule. The model was further tested at the construction site case study and proved effective. The authors highlighted that the actual location measurement component of the model adds a control dimension throughout the comparison of the planned protective measures and the ones actually erected on site. In 2007 the authors (Jang and Skibniewski, 2008) introduced a tracking system that used radiofrequency and ultrasound for the localization of materials to overcome the limitations of previous Radio-frequency identification (RFID)- and GPS-based technologies. The emphasis was on precast concrete, steel girders, Polyvinyl chloride (PVC) pipes, i.e., bulk materials. In the same year, authors (Teizer et al., 2007) presented Ultra-Wide Band (UWB), used for real-time location sensing and resource tracking, with a focus on monitoring the safety, labor, and resource on the construction site. The authors state that further research is needed to explore UWB's full potential in the construction industry. The next innovation regarding the safety on the site was proposed in 2009 which is a system comprising of a mobile sensing device based on hybrid sensors that detect the worker's movement and informs the computer if they are approaching dangerous places (Lee et al., 2009). In the following step, it sends the information to software interpreting that information using a transmitter and repeater. The improvement of the system in terms of identification of workers who are in danger was suggested as further research. An extremely interesting method was introduced in 2010 by authors (Son and Kim, 2010) which automatically recognized and modelled 3D structural components by using 3D data and colour. The process consists of four parts: acquiring 2D image and 3D data, recognition of 3D structural components, the building of the as-built model, and assessment of the project's progress. As further research, the authors state that the proposed modelling method will be expanded to perform recognition of a number of types of structural materials, including reinforced concrete, masonry, and timber. In 2011, two methods for as-built status in construction were presented in (Golparvar-Fard et al., 2011) where the first one uses unordered photos of the construction site with analysis of Structure from Motion (SfM) and the second one uses 3D laser scanning and analysis of the as-built point clouds. The results of 8 sets of 3D spatial models show that the point cloud generated by the laser scanner shows higher accuracy than the image-based point cloud models. As further research directions, the authors list additional research regarding algorithms that fully extract conventional or parametric CAD objects from laser scanners or image-based point cloud models and optimizing the SfM algorithms for generating higher-quality point cloud models with less computational costs. In a study (Kim et al., 2013b), the construction progress measuring method was introduced that uses 4D BIM with 3D data obtained by remote-sensing technology and comprises three parts. The first part aligns as-built data with the as-planned model, the second one matches the as-built data to BIM and the third part revises the as-built state with the whole process resembling the aforementioned method (Son and Kim, 2010). Also, the authors state that the as-built realization can help in determining finishing dates and progress measuring. As further research directions, the authors mentioned extracting more information from thermal images and integrating it with color attributes from BIM. In 2012, a framework using virtual reality (VR) for streaming data from sensors to a real-time data visualization platform was presented (Cheng and Teizer, 2013). The biggest contribution of the framework is the visualization of workers' close calls (misses), i.e., dangerous situations and positions of workers can be visualized in advance and therefore avoided. The effectiveness of the system was tested, but the authors state that further analysis to measure its impact on existing work and training practices is needed. In 2013, authors (Kim et al., 2013a) presented an automated 4D CAD model-updating method. The method uses image processing-based automated project scheduling that implies site-image acquisition, construction progress identification, and a 4D CAD development. In 2015, the use of thermal images was introduced into the automation of construction monitoring when the paper (Zhang and Pazhoohesh, 2017) presented a new method consisting of three parts. The first part implies collecting thermal and original images from the Infrared camera, the second one uses wireless sensor networks to estimate the position of images captured in part one, and the third one implies the automated update of the 3D plan in BIM. The authors highlight that a case study involving the construction of the deck segment of a cable-stayed bridge showed that the image processing achieved 92 % accuracy and that the model was successfully developed. Also, they state that the 92 % success rate for progress identification can be improved by using an intelligent image-selection algorithm. Authors (Ren et al, 2017) presented in 2017 an innovative vision-based method for automated monitoring of the utilization rate of on-site construction equipment. First, the positions of equipment are localized and tracked in video frames, and their locations are extracted from those videos. In the following step, the locations of equipment are compared with locations of work zones so the utilization rate of equipment can be measured. The method proved effective and the authors state that it is particularly suitable for remote construction sites where it is not always possible for engineers to collect data. In the same year, authors (Rebolj et al., 2017) presented point cloud quality requirements for Scan-vs-BIM-based automated construction progress monitoring where the proposed methodology implied the definition of building element classes and the definition of point cloud quality parameters. The proposed method provides an objective tool for the comparison of point clouds and presents the first framework for comparing the capabilities of various technologies and evaluating them for specific object identification purposes. In 2018, an automated continuous construction progress monitoring was presented which uses multiple workplace real-time 3D scans (Pučko et al., 2018). It is based on the comparison of 4D as-built BIM and 4D as-designed BIM models where the point clouds are collected from the worker's helmets. The authors state that in further research, the worker helmets should have a subsystem for precise positioning and orientation in order to achieve automation of partial point cloud registration. Nowadays, unmanned aerial vehicles (UAVs) are more commonly used for obtaining information regarding construction site. So, in 2020, a study was conducted in which authors used UAVs to monitor the construction process of a commercial building (Kielhauser et al., 2020). The method used is based on the detection of structural elements of the building, in specific the sectional approach, calculation of concrete volume, measurement of height and distance, and the detection of defects. The general process comprises three parts: data collection, data processing, data analysis and the method of automated monitoring has shown practicable. Authors (Asadi et al., 2020) went a step further by integrating unmanned ground vehicle (UGV) with an UAV. The system provides an effective solution for most locations since the UAV covers the cluttered scenes inaccessible to the UGV. The UGV can autonomously move through space while the relative position of the UAV is continuously estimated, and it serves as an eye to the UGV while following it. Following the current sustainability trends, in 2021 a real-time automated monitoring system for managing hazardous pollutants on the site, such as noise, vibration, and dust, was presented where a sensor network receives the data of pollutants from sensors. The system is expected to prevent conflicts among construction companies and residents near construction sites (Kang et al., 2021). The main achievements in the monitoring phase of the construction project lifecycle are chronologically shown in Fig. 5.

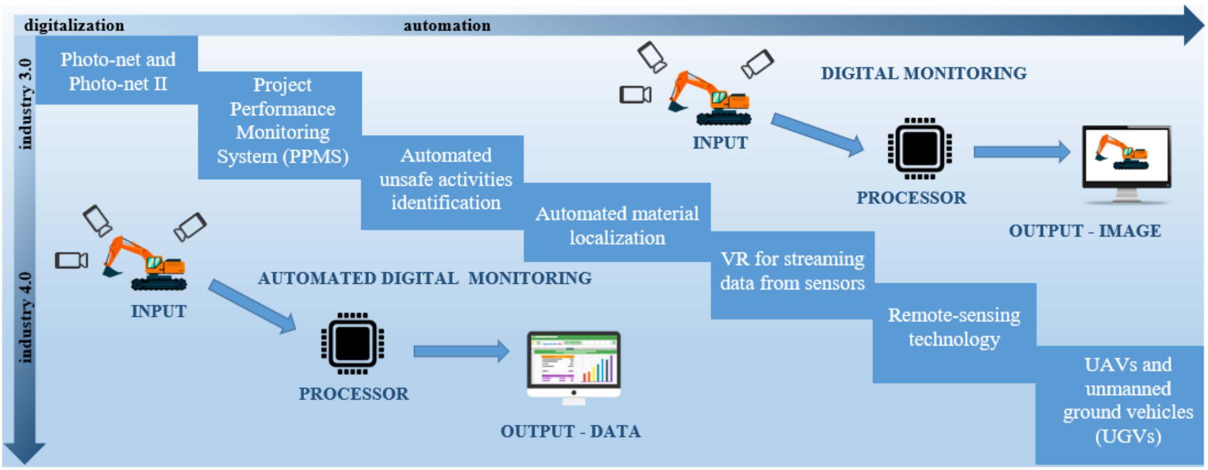

FIG. 5: Chronological milestones of digitalization and automation achievements in the monitoring phase.

6. DISCUSSION

Throughout this literature review of digitalization and automation achievements in the construction project life-cycle phases, certain milestones in the development of each phase have imposed themselves. Also, it is obvious that some life cycle phases are developing rapidly in comparison to others. The disproportion of the digitalization and automation adoption is perhaps the most obvious when other phases compared with the initiation phase since it is mostly dependent on BIM and has started to develop more significantly after BIM's wider application. The initiation phase is, as it was anticipated and structured as the DH1, found to be at low digitalization and automation adoption level. This is primarily due to the fact that it is still mostly based on human interaction and brainstorming, and is consistent with the fact that it is dependent on BIM and its capabilities in the initiation phase, which are still very limited. While the design phase is perhaps the one with the longest period of development since the aspiration to move the engineering drawings from paper to computer was one of the first ideas of digitalization in construction. Therefore, was the design phase dependent on the development of the computer and its wider application. As anticipated in DH2, the design phase has a high level of digitalization with a low level of automation which is in line with the fact that it is also mostly dependent on BIM and its development, but still requires large amounts of input data and quality information, to begin with the design. Similarly, the scheduling phase is also in line with DH2, even though it has not been developing for as long as the design phase, it is still at a level where detailed input data is required for the generation of a quality schedule. Also, the design and scheduling phase are interconnected because it is nowadays possible to transform a design BIM model into a scheduling plan of activities. The execution phase is very specific since the construction robots and automated sites have allegedly appeared during the 1980s and 1990s but it was the case in Japan only. Perhaps the key problem with the execution phase is the high level of visualization and conceptualization but with a very low level of actual effectuation and creation of such robotics and automated systems. A very large number of single-task robots have been developing lately, but they still require human control and interaction and are mostly limited to only one task where execution still lacks an integrated automated system that could handle multiple operations. This confirms the anticipation in DH3, which states that execution and monitoring have a low level of digitalization with a higher level of automation, while they are at the same time the phases with the most potential. The monitoring phase confirms this potential since its development has been proliferating in the past years, mostly influenced by introducing Construction 4.0 technologies and their integration with them.

7. CONCLUSION AND FUTURE DIRECTIONS

This paper presented a literature review of digitalization and automation achievements in the construction project life-cycle phases, i.e., the initiating phase, the design and planning, and execution. Since the research questions, 1-3 concerned each phase separately, to answer RQ1, chapter 3, i.e., digitalization and automation level in CP's initiation was introduced where it was found that BIM summarizes the costs, duration, necessary stakeholders, waste generation, etc. which provides a basis for whether to go on with the project. Therefore, is BIM a crucial element in the initiation of a project.

With the aim of answering RQ2, chapter 4 was introduced, i.e., digitalization and automation level in CP's design and planning, where it was found that BIM already has a high level of innovations and development regarding the design and planning phase. Despite that, since the reduction of needed time is imperative nowadays, it is expected that an even higher level of automation would probably be required with a decreased need for input quality and level of detail.

To answer RQ3, chapter 5 was introduced, i.e., digitalization and automation level in CP's execution. It was found that the automation of construction execution does not enhance monitoring since the automation of monitoring is developing much faster. Also, it has already reached the level of independence while robotics on the construction site is still mostly one task robots that are not autonomous and human control is required. Research questions 4-6 concerned the entire life-cycle of a project, so it can be said that they are concluded based on the whole paper.

In order to answer RQ4, the challenges of each life-cycle phase of the project were analysed, and it was found that the main challenges of automating the project's life-cycle are the differences among each phase which require specific software, specific equipment, and knowledge from the project team members. An additional challenge is the complexity of large construction projects, which are not to that extent supported by current achievements. Finally, perhaps the fundamental challenge is the further automation of the execution phase, which would eliminate the need for constant human control and interference.

With RQ5 it was aimed to determine the main benefits that digitalization and automation have brought to the project's life-cycle and it was concluded that the main benefits are decreased need for manual work and constant human control, shortened duration of construction, increased quality of the project, and standardization while increasing the quality and decreasing the duration of the project.

The RQ6 was introduced in order to answer how are levels of digitalization and automation interconnected among construction project life-cycle phases. Throughout the analysis of automation and digitization levels of each phase, it was found that they are mostly interconnected among project life-cycle phases through the use of BIM. This is because the initiation phase includes surveys and studies resulting in the draft investment program and solution. The following phase, i.e., the design phase, mainly leans and streams towards the BIM concept, which enhances and enables the generation of schedules to cover the aspects of planning. Finally, the BIM model is further used in execution as the main guideline of the project and in monitoring for the comparison of the current state with the BIM model.

The topic of digitalization and automation in construction projects and in the AEC industry in general, is mainstream and has galloping development. Based on the findings of this study and the current state of knowledge on the subject, similar research should be conducted in the near future to reveal advancements in development and even predict higher, more sophisticated levels of digitalization and automation in construction projects. As well, it would be interesting to test hypotheses from this study in multiple construction project environments and conduct research on various project stakeholders' anticipations regarding digitalization and automation in project life-cycle phases.

ACRONYMS AND ABBREVIATIONS

TABLE 2: Acronyms and abbreviations.

AEC	Architecture, Engineering and Construction
AM	Additive Manufacturing
API	Application Programming Interface
AR	Augmented Reality
ADC	Automated Data Collection
BD	Big Data
BDA	Building Design Advisor
BIM	Building Information Modeling
BPM	Building Project Model
CIRC	Computer Integrated Road Construction
CAD	Computer-Aided Design
CP	Construction Project
DVS	Default Value Selector
DfS	Design for Safety
EU	European Union
GA	Genetic Algorithm
GIS	Geographic Information System
GPS	Global Positioning System
HVAC	Heating, Ventilation, and Air Conditioning
IPT	Intelligent Parametric Templates
IBM	International Business Machines
ISO	International Organization for Standardization
IPMA	International Project Management Association
IoT	Internet of Things
KBES	Knowledge-Based Expert System
LOD	Level of Detail
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
MIT	Massachusetts Institute of Technology
MOSCOPEA	Multi-Objective Scheduling Optimization using Evolutionary algorithm
NDSM	N-Dimensional Project Scheduling and Management system
OSM	Object Sequencing Matrix
OSYRIS	Open Systems for Road Information Support
PVC	Polyvinyl Chloride
PMI	Project Management Institute
PPMS	Project Performance Monitoring System
RFID	Radio-frequency identification
SGE	Schematic Graphic Editor
SfM	Structure from Motion
UWB	Ultra-Wide Band
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
VR	Virtual reality
WBS	Work Breakdown Structure

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