DOI: https://doi.org/10.14256/JCE.3575.2022

Građevinar 5/2023

Primljen / Received: 1.8.2022.
Ispravljen / Corrected: 28.12.2022.
Prihvaćen / Accepted: 9.2.2023.
Dostupno online / Available online: 10.6.2023.

Construction project organisation for 3D printing technology

Authors:

Nikola Spicek, MBA
BMW Group, Germany / Alma Mater Europaea ECM
nspicek11@hotmail.com
Corresponding author

Prof. **Mladen Radujkovic**, PhD. CE
Alma Mater Europaea ECM, Slovenia
mladen.radujkovic@almamater.si

Prof. **Miroslaw J. Skibniewski**, PhD. CE
University of Maryland, College Park, USA
mirek@umd.edu

Subject review

Nikola Spicek, Mladen Radujkovic, Miroslaw J. Skibniewski

Construction project organisation for 3D printing technology

The integration of three-dimensional (3D) printing technology into construction projects potentially yields many benefits, such as reduced site labour requirements, safer manoeuvring of project deadlines and budgets, and more effective waste management. However, the momentum of technology is not as expected owing to the lack of standardised processes and methodologies, and challenges imposed by the new technology. The organisational structure of such projects must be comprehensively studied. Studies on construction projects using the 3D printing technology are lacking. This study reviews the existing studies and three different case studies in Germany, United Kingdom, and United States of America to explore the primary differences between the roles, responsibilities, and interactions of key project participants within the organisational structure of construction projects using the 3D printing technology. The roles and responsibilities of clients/investors, project manager/construction managers, architects, structural engineers, quantity surveyor/project supervisor, and contractors/main contractors have been considered. Therefore, all features of the role of key participants and responsibilities to the new momentum created by this emerging technology must be aligned; otherwise, the combination of new technology and conventional organisation will reduce the value created by the new technology.

Key words:

3D printing technology, project organisation structure

Pregledni rad

Nikola Spicek, Mladen Radujkovic, Miroslaw J. Skibniewski

Organizacija građevinskog projekta za tehnologiju 3D ispisa

Integracija tehnologije trodimenzionalnog (3D) ispisa u građevinske projekte potencijalno donosi mnoge prednosti kao što su smanjeni zahtjevi za radnom snagom na gradilištu, sigurnije upravljanje projektnim rokovima i budžetom te učinkovitije gospodarenje otpadom. Međutim, zamah tehnologije još uvijek nije prema očekivanjima zbog nedostatka standardiziranih procesa i metodologija, ali i zbog izazova koje nameće nova tehnologija. Organizacijsku strukturu takvih projekata potrebno je sveobuhvatno proučavati. Ova studija nudi pregled postojećih studija i triju različitih studija slučaja u Njemačkoj, Ujedinjenome Kraljevstvu i Sjedinjenim Američkim Državama u cilju istraživanja primarne razlike između uloga, odgovornosti i interakcija ključnih sudionika projekta unutar organizacijske strukture građevinskih projekata u sklopu kojih se primjenjuje tehnologija 3D ispisa. Razmatraju se uloge i odgovornosti klijenata/investitora, voditelja projekta/voditelja izgradnje, arhitekata, građevinskih inženjera, nadzornog inženjera i izvođača/glavnih izvođača. Dakle, moraju se uskladiti sva obilježja uloge ključnih sudionika i odgovornosti stvorenih tom tehnologijom u nastajanju. U suprotnome će kombinacija nove tehnologije i konvencionalne organizacije smanjiti vrijednost koju pruža nova tehnologija.

Ključne riječi:

tehnologija 3D ispisa, organizacijska struktura projekta

1. Introduction

Recent studies have proved that employing the three-dimensional (3D) printing technology may offer many advantages, including reduced amount of material and energy usage [1-4], onsite production with fewer resource demands, and lower related CO_2 emissions over the complete product life cycle [5] than those of conventional techniques. In addition, it stimulates changes in labour structures, including a safer working environment, and helps achieve more digital and localised supply chains [6]. From an architect's point of view, the 3D printing technology can shorten design and development cycles and allow customers to co-design products that can impeccably fit their demands and ambitions, empowering the realisation of complex designs and quickly steering design changes [1-4, 6].

The 3D printing technology is an automated production technique with layer-by-layer control, which has been improved in recent years. This technology has been applied in the manufacturing industry for decades and has recently been applied in the construction industry to print houses and villas [7]. A systematic review shows that the improved 3D printing technology can be used to print large-scale architectural models and buildings [7]. However, the capacity of this technology is restricted by the lack of large-scale execution, development of building information modelling, need for mass customisation, and life-cycle expense of printed projects [7].

Although the 3D printing technology has a massive potential, it has not been sufficiently adopted to the market [8]. Nevertheless, 3D printing can be remarkably applied in the construction sector as it offers certain advantages over the conventional construction technologies. In addition, the standardisation of the process, classification of materials, and education of both city administration and experts involved in the preparation of construction permit documentation are considered as prerequisites [9]. Moreover, the use of 3D printing technology might positively influence some of the key features in construction, such as the project cost and time [10], labour cost volume [11-13], and construction and demolition waste management [14]. Obviously, the new construction technology should not only advance construction processes but also help construction approach the current paradigm of aligning people, planets, and profit components.

A feasible answer is the implication of new technologies and solutions for managing construction projects. Technology readiness (TR) is manifested in consumers' yearning to adopt and use innovative technologies to achieve their daily/business goals [15]. The acceptance of a new technology requires the accomplishment of technology acceptance model principles, which assumes that an individual's information system acceptance is strongly influenced by (1) perceived usefulness and (2) perceived ease of use [16]. However, as construction is a completely project-oriented sector; thus, the following questions arise: what is the status quo with the acceptance of an innovative technology in the project organisational structure? and How does it change the structure itself, and roles, responsibilities, and interactions among key participants of such projects?

The question that remains intensely unexplored is how to avoid scenarios with the new 3D printing technology and existing organisation; the past experiences have revealed that major changes or advancement of technology claims for advancing or adjusting the organisation and management to leverage all advantages.

According to the International Organisation for Standardization (ISO), organisation is a temporary structure that defines the roles, responsibilities, and authorities of projects. Individuals are assigned names for specific roles in the project organisation. The project organisation should establish clear governance and management lines, and be approved and communicated to all project stakeholders [17]. The project organisation should be defined in sufficient detail such that everyone can comprehend their role and responsibilities, and roles and responsibilities of other colleagues. Responsibilities should be consistent and understandable throughout the project [17]. Missing any of the details might cause situations and scenarios that negatively influence the project ecosystem and obtained results. Therefore, the official project management methodology issued by the European Commission (PM^2) suggests a clear and transparent project organisation with an agreed and approved structure, roles, and responsibilities precisely determined by the RASCI matrix [18]. However, in addition to global PM standards, key participants and their roles, responsibilities, and interactions within a construction project are defined in each country by national/local legislation and/or regulation. Owing to specific historical paths and economic frameworks, major differences in regulation and practices across regions and countries exist, and practitioners manage their roles with respect to national regulations and incorporation of proven global knowledge. While applying the above to construction projects, we learned that it works; however, the effects of changes in construction technologies to 3D printing on the roles, responsibilities, and interactions of key participants within the project organisation structure must be studied.

The existing studies did not provide any useful information as to construction project organisations for the 3D printing technology. Therefore, in this study, the existing studies were completely reviewed and results reported in other sectors that have previously applied the new technology were compared. In addition, three different explanatory, descriptive case studies from Germany (formwork 3D printing of stairs), the United Kingdom (manufacturing wall sections), and the United States of America (residential building), are explored, while a parallel is drawn with the scenery and task of the project organisational structure in construction projects built using a conventional method. The aim was to investigate the effect of this change in the project team members, and its effect on the roles, responsibilities, and interactions among key participants of construction projects utilising the 3D printing technology. Therefore, the main research question has been defined as follows: How are the roles, responsibilities, and interactions of key participants in projects using the 3D printing technology changing compared to the conventional model? To answer this question, the following three sub-questions were specified:

1. What has previously been identified as to the roles, responsibilities, and interactions of the key participants in construction projects using the 3D printing technology?
2. What deductions as to the roles, responsibilities, and interactions of key participants in projects using the 3D printing technology can be drawn compared to the conventional construction models?
3. Is it necessary to adapt existing project management methods/project organisation structures to this new technology?

The results revealed that roles (client, project manager, quantity surveyor, structural engineer, contractor) significantly affect projects using the new technology. In addition, the new technology will affect the related jobs, responsibilities, and competences.

2. Methodology

Figure 1 shows that this study first reviews the existing studies and their key findings. As the studies conducted on the organisational structure of construction projects using the 3D printing technology are scarce, examples from other industries, such as the IT and public sectors were considered. In addition, other selected elements of organisational structure of construction projects, such as success factors, project team dynamics, working conditions within project teams, and stress, were observed. Moreover, these findings can be applied to construction projects that use the 3D printing technology.
The second part of this study presents three different case studies based on projects performed in Germany (3D formwork printing for stairs), the United Kingdom (manufacturing wall sections), and the United States of America (residential building, observed only on the outer and inner walls). Interviews were conducted with various project participants, and conclusions were summarised by combining project documentation, such as personal observations after interviews with project team members and leaders. Furthermore, few projects used the 3D printing technology that were in the initial phase. We learned that the United States of America and China were leading countries and similar projects could be observed in the United Kingdom, Germany, France, and Italy in Europe and India, Japan, and Korea in Asia partially follow the advancing countries [35].
Targeted projects for this study were selected based on the similarity of their organisational structures appropriate to the influences of different practices and regulations. They have all been recently accomplished in developed countries as trend bearers, while in all cases, the 3D printing technology is recognised as a potential alternative to the problems of conventional construction projects. The literature review and findings are separately presented; subsequently, the results are discussed together. Finally, the assumptions, limitations, and directions for further research, followed by the conclusions are presented.

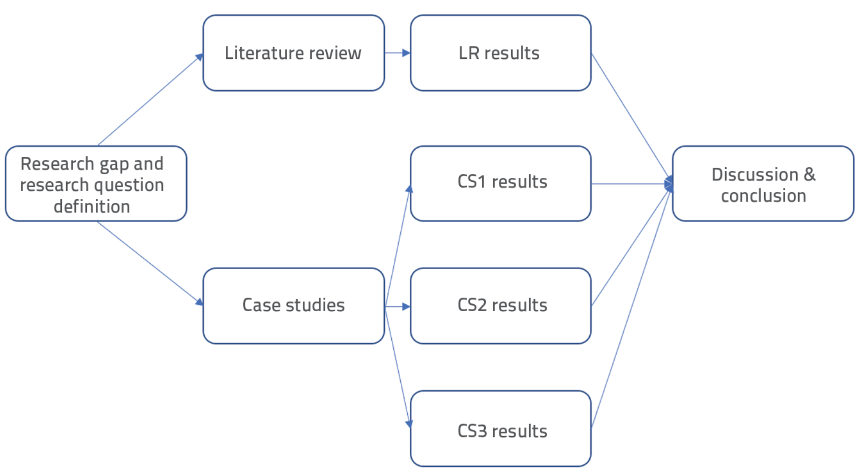

Figure 1. Research methodology diagram

3. Construction projects using the 3D printing technology

3.1. Strengths, weaknesses, challenges, and critical success factors

During the construction technology development cycle, the use of prefabrication was one of the milestones, offering considerable improvements. However, appropriate criteria for applicability assessments to certain building projects is lacking [19]. Decisions to use prefabrication are still mostly based on the anecdotal evidence or merely cost-based evaluation when comparing diverse construction methods [19]. Nevertheless, it could be an important source for lessons learned for the existing 3D printing technology, such as missing standardisation, backbones, and reference examples of successful construction projects that used the 3D printing technology.
Moreover, the 3D printing technology has been rapidly developed in recent years; in addition, it has been implemented on prototype building and bridge construction projects [20]. However, several 3D printing-based solutions are in the laboratory experimental stage; consequently, successful adaptation of 3D printing in the construction industry must be examined [20]. Indeed, nine potential factors and thirty-two experiments to adopt the 3D printing technology in construction projects were reported, where the key factors in guaranteeing the successful application of the 3D printing technology in construction are "technology compatibility", "supply-side benefits", and "complexity" complexity [20].
Furthermore, potentially close area about "additive manufacturing" references technologies that grow 3D objects one superfine layer at a time where each successive layer bonds to the

preceding layer of melted or partially-melted material. The existing studies primarily consider the implementation process of additive manufacturing as sociotechnical studies in this field are lacking [21]. It focuses on the need for existing and potential future additive manufacturing project managers to develop an implementation framework to guide their efforts to adopt this new and potentially disruptive technology [21]. Sonar et al. [22] also contributed to identifying additive manufacturing factors from a generic perspective, whereas context-specific factors require further investigation [22]. The results reported in [21, 22] reveal that the topic of roles, responsibilities, and interactions of key participants in construction projects that use the 3D printing technology is a moderately new subject.

3.2. Collaboration between construction project key participants

The collaboration between project participants in conventional construction projects can be potentially transferred to projects that use the 3D printing technology. For example, one study identified the enablers, that is, the governing factors of collaboration [23]. Another study explored the processes through which the values relating to construction projects, with reference to sustainability, were established and operationalised [24]. The project temporary multi-organisation (TMO), as a shifting, multi-goal, power-based coalition, encourages fluctuations in the values employed to drive the project as it develops and makes the evaluation of performance highly challenging [24]. As the values are human-defined, they are grounded in culture [24]. Moreover, the comprehension of culture as an operative construct in the project value system helps explore and develop concepts and practices associated to the sustainability of construction projects [24].
Although the effect of advancing membership and power structure of the project TMO should be examined in projects that use the 3D printing technology, cultural factors in the sustainability of construction projects must be considered.
In addition to TMO, the effect of participants' values on the construction sustainability should be investigated in projects that use the 3D printing technology. Indeed, technology is one of the key components of success in construction projects. However, even the lates of high technology itself cannot guarantee success. Many practical evidences proves that different users deliver different results while using the same technology, which addresses the role of people, their competence, and their organisation in a project. The only scenario in which modern technologies embrace adequate organisation and management will deliver a high-level success.

3.3. Roles, responsibilities, and interactions of key participants in organisational structure of projects

Many project management standards or methodologies, such as ISO and PM², laws and regulations of countries where the case studies took place, and various aspects of the existing studies were analysed to define the roles, responsibilities, and interactions of key participants in the organisational structure of construction projects. According to the ISO, one person can take no more than one role, and their responsibilities are thoroughly described [17]. The ISO21502:2020 guidance provides a globally known example for organising the roles and responsibilities of project sponsors, managers, officers, and stakeholders, as shown in Figure 2 [17].

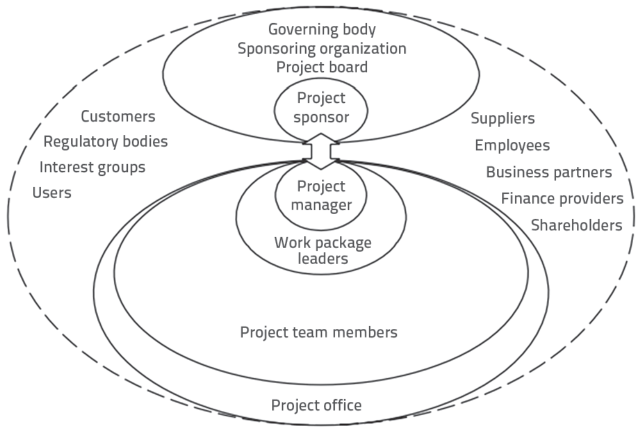

Figure 2. An example of potential project stakeholders [17]

Moreover, PM² states that one project team exists that is made up of people who take on the roles defined in the performing, managing, and directing layers, which must work together as a team to make the project a success (PM², 2018). Figure 3 illustrates the project organisational layers and roles according to PM². Close collaboration and communication between the business manager (BM) and project manager (PM) is paramount to a project's success (PM², 2018).

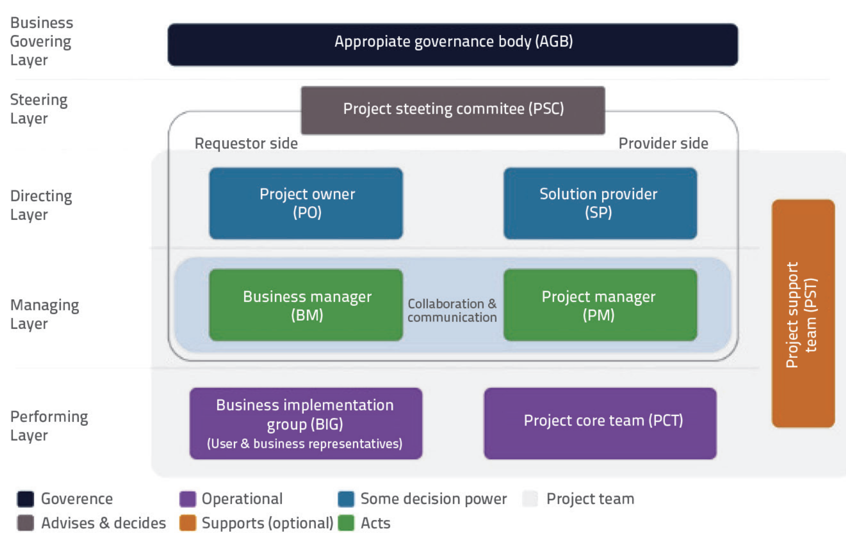

Figure 3. Project organisation: layers and roles [18]

Therefore, organisational structure, and key roles and responsibilities are recognised as key elements of successful project management. Despite variations in the structural graph, a more detailed analysis could confirm alignment in the key concepts and mindset, while details might be tailored in relation to project features and environment.

As for the laws of individual countries, for example, German law can be divided into private and public laws, which are distinguished by different legal principles and authorities, where law regulates the legal relationships between equal legal subjects and has the task of protecting the legal interests of the individual [25]. This is done by the Civil Code (BGB), which states that in addition to architects and engineers, many other participants are involved in construction [25]. Among other stakeholders, the owner/client, architect, and various engineering specialists, including structural engineers, engineers for technical building equipment, sound insulation and room acoustics engineers, civil and traffic systems engineers, geotechnics engineers, and surveyors participate in the construction projects [25].

In contrast to Germany, where the law is codified and thus a uniform and general construction contract law exists that is regulated by law in the BGB and concretized by the VOB/B, a comparable legal basis for contracts in the construction industry is completely lacking in England [25]. Nevertheless, clients, designers, contractors, and others involved in construction works have duties under the Construction (Design and Management) Regulations (CDM 2015) [26]. The stakeholders outlined in CDM regulations are client - the person for whom a project is carried out; principal designer - designer with control over the phase before the construction of the project (appointed by the client); designer organisation or individual that prepares or modifies a design for a construction project or engages or directs another to do so; principal contractor–organisation or individual that coordinates the work in the construction phase of the project involving more than one contractor such that it is performed in a manner that guarantees health and safety; and contractor–any person who directly employs or hires construction workers or manages construction [26].

The United States has three branches of government: judicial, legislative, and executive. Each branch contributes to laws governing the design and construction contracts [27]. A construction project may be subject to different laws depending on whether the project is private or public, country in which the project is located, and type of project [27]. Construction law in the United States is the area of law that deals with the regulations, guidelines, and requirements in the construction industry and includes the elements of contract law, property law, commercial law, labour law, and many others where construction law is essentially a library of regulations that govern how a construction project must be executed and who is liable if something goes wrong [28]. According to the construction contract interpretation, the construction project participants include owners, architects/engineers, construction managers, contractors, subcontractors, and suppliers [29], whose responsibilities and domains of work do not considerably deviate from the roles and responsibilities described in Germany and the United Kingdom.

In all selected countries, within the regulations, the key participants and their roles and responsibilities are roughly defined with minor variations.

4. Case studies

4.1. Research approach

Key participants of the construction projects were defined as presented in [30], because the provided definitions best matched the key participants observed in the three case studies and best corresponded to the consensus stated for the selected countries and analysed methodologies. However, only rounded participants were observed in the order of client (hereinafter referred to as investor), project manager (construction management), architect, structural engineer, quantity surveyor (hereinafter referred to as project supervision), and contractor (main contractor), as shown in Figure 4. Mechanical and electrical engineers were omitted, as their work was performed according to the conventional construction method in all three case studies, and their roles, responsibilities, and interactions with other key participants were assessed as unchanged. The selection of key project participants to be focused on is noticeable and in accordance with the regulations of each country and estimated according to the ISO standards and PM² methodology, as described in Subsection 3.3.

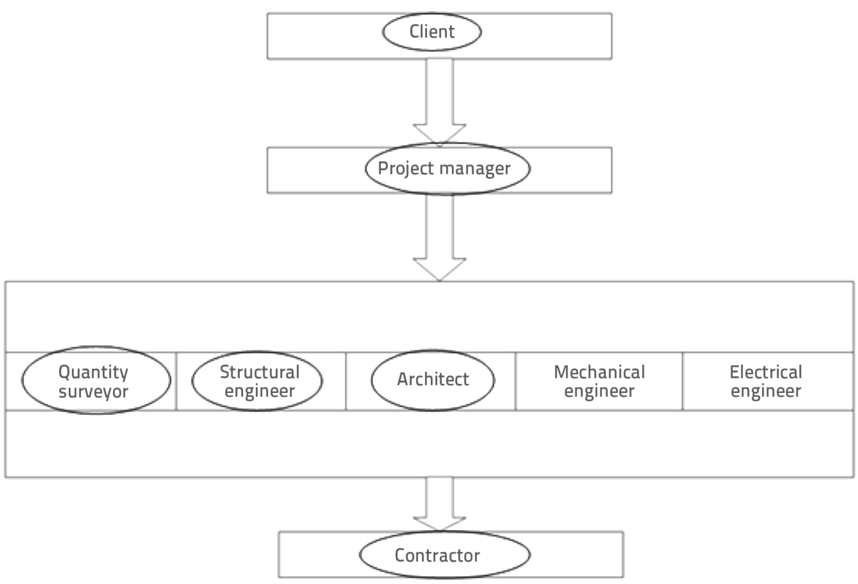

Figure 4. Typical team structure for conventional building projects [30]

Figure 5. 3D printed formwork of the staircase [31]

Figure 6. Appearance of the staircase after removing the 3D printed formwork [31]

4.2. Case studies description

4.2.1. Case study 1: 3D printed formwork for stairs - Leipzig, Germany

The first case study considers the 3D printing of formwork for stairs as part of the construction of a new bank building in Leipzig, Germany. It is a complex project perfectly suited for the integration of 3D printed formwork, whose ultimate purpose is conceived as a curved arch of the foyer staircase. This is a single-shell formwork masonry (monolithic construction). It was decided to use 3D printing because a high-precision formwork was needed to provide the staircase with a smooth and even curve. Because the design of the staircase has triple curvatures, 3D printing was the obvious choice because the conventional production of such a formwork would have been incredibly costly. In addition, a low precision was likely to be achieved. Alternative/conventional approaches to implement the project would be using the conventional formwork construction. This would require the strips to be glued together. Additional quality assurance in view of weathering influences was enabled by a homogeneous material composition. Seven formlining parts were created from sand with a wall thickness of only 21 mm using the powder-binder jetting process. Subsequently, these were milled and coated with the modelling dimensions. Moreover, formwork elements were painted to seal the surface. CAD data were created as internal data by a 3D printing company expert. The printed material for the printing of seven components was sand (FDB). Epoxy resin, sanding, and painting were used for finishing. The process of finishing increased dimensional stability and yielded a smooth surface. A visual representation of the 3DP formwork; the product after removing the 3DP formwork is shown in Figures 5 and 6.

4.2.2. Case study 2: manufacturing wall sections – United Kingdom

The second case study represents 3D printing (manufacturing) of wall sections to be assembled into a residential structure in the United Kingdom. It was designed by leading industrial designers with the desire to create a free-form functional yet low-cost structure without moulds. Clearly, an alternative was manufacturing those components using moulds. Building drawings/models were created using a 3D modelling software (could be parametrically based), such as Rhino and Solidworks. The project contractor organised a construction team consisting of a 3D printing service provider, site constructor, and building service provider. Both on- and off-site printing methods were used in the construction process. The printed material was extruded, which is a process that consists of forcing a formable material to pass through a die having the cross-section of the part to be obtained [32], and deposition of cement-based mortar to print a total of six wall components with different exterior shapes and cavities for services, which was in accordance with the 3D printing system, material, and printed wall section, as shown in Figure 7. After printing, the necessary treatment was applied to guarantee as-planned integration of the printed components.

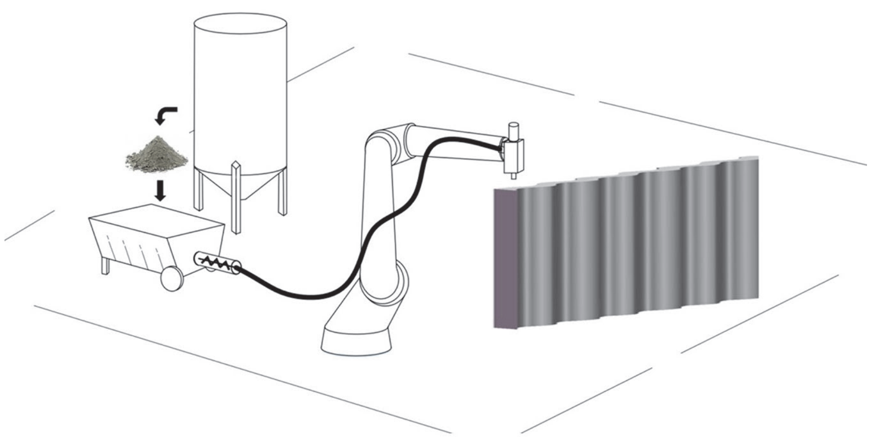

Figure 7. Redrawn according to the description of the project contractor

4.2.3. Case study 3: residential building - Arizona, United States

The third case study describes the Habitat for Humanity Project. It is 3D-printed house in Arizona, next to three similar houses built using the conventional construction methods. The focus of this case study was on exterior and interior walls (printed in "one go"). It is a house with the understandable function of someone living in it in the future; thus, it did not differ from conventional constructions. This was performed using a COBOD printer (headquarters in Denmark). Furthermore, European companies provided other instructions; thus, the strategy and operations were similar to projects built on European grounds. The difference was in the "day-to-day" processes that these companies have in the development of technology. However, this example showed that no one can determine the best approach/best solution, and every company improves various aspects of the technology, such as the software, materials, and hardware. Consequently, no single best practice exists, and companies (clients) receive quality feedback, usually only from the group from which they bought or rented a 3D printer. Therefore, if the printer is from COBOD, it is extremely likely to use the COBOD techniques. The company (client) was researching innovations, and in this case, they experimented with their other projects, which resulted in the decision to print using the 3D printing technology. This case was compared with three similar neighbouring houses built of concrete using conventional construction methods. A general description of the CAD creation process can be defined as a procedure to precisely model the part to be built. However, the current process is extremely dissatisfactory, and the whole purpose of the new technology is to rethink the paradigm of construction from scratch. Indeed, an architect dreams of a design that is converted into a 3D model by slicing the model into Step file for large-scale printers or STL file for 3D printer Dot, which is sent to the printer according to directional 5.5 instructions, layer-by-layer, is used to deposit the concrete. As for printing materials, concrete is printed. In practice, it is mortar; thus, it is less than 2 mm aggregate; however, tag concrete, although technically incorrect, is a common expression. Moreover, the mortar mix and printing speed must be appropriate for weather conditions [33].

The entire house (interior and exterior walls) was printed layer-by-layer, as shown in in Figure 7, in full swing (modelling extraction). Only paint (for aesthetic reasons) and sealing (for technical reasons) were used for finishing; however, it was a monolithic structure in the end. Most of the concrete was exposed, without plaster, and was not smooth, as shown in Figure 8. There were some cracks that required post-processing and sealing gaps for aesthetic and technical reasons. As the concrete was extruded, some splatters appeared. The procedure was not a highly automated process; however, it was a highly labour-intensive process that required many steps of human intervention. The goal is for people to learn and automate the procedure; indeed, beginning the process is difficult; however, once the entire process is completely understood, a button must be pushed only.

Figure 8. A 3D printer printing a three-story apartment building (exterior and interior walls) [33]

Figure 9. Three-dimensional printing of exterior and interior walls, left in their original layers [33]

4.3. Case studies - Questionnaire for the 3D printing process

This case study consisted of a questionnaire, project documentation, and post-questionnaire to communicate with the key project participants. Table 1 presents the questions regarding the employment of 3D process. Moreover, the answers are summarised in Section 5 for each case study separately.

Table 1. Case studies - 3D printing process questionnaire

1.	What are the advantages and future potential for 3D printing based on conclusions from this case study?
2.	What are possible further research & development steps based on this case study?
3.	Overall, what were the biggest challenges in this project?
4.	For which application areas can 3D printing be recommended based on conclusions from this case study?
5.	What are the greatest strengths and the greatest weaknesses of 3D printing for concrete casting based on this case study?

Table 2. Case studies - 3D printing organisational structure questionnaire

1.	How should the example of ideal project team for construction projects that use 3D printing technology look like and what is the ideal composition of the project team members?
2.	What is the main difference between the role of the client / the investor in projects that use 3D printing technology compared to the conventional method of construction?
3.	What is the main difference between the role of the project manager / construction manager in projects that use 3D printing technology compared to the conventional construction method?
4.	What is the main difference between the role of the architect in projects that use 3D printing technology compared to the conventional way of building?
5.	What is the main difference between the role of the structural engineer in projects that use 3D printing technology compared to the conventional method of construction?
6.	What is the main difference between the role of the quantity surveyor / project supervision in projects that use 3D printing technology compared to the conventional method of construction?
7.	What is the main difference between the role of the contractor / main contractor in projects that use 3D printing technology compared to the conventional method of construction?
8.	Regardless of the project team, what is the effect of changing the construction method from a standard method to projects that use 3D printing technology in the context of the manpower necessity?
9.	What is the difference in terms of project team costs, manpower costs and suppliers' costs in projects that use 3D printing technology compared to standard construction?

4.4. Case Studies - Questionnaire for the project organisation structure, roles, and responsibilities

Table 2 presents the questions regarding the project organisational structure, roles, and responsibilities. Moreover, the answers are summarised in Section 5 for each case study separately.

5. Results

5.1. Literature review

Many studies have been conducted on appropriate organisational structure of projects, that is, the best balance of roles, responsibilities, and interactions, which considered project success factors [10], collaboration between construction project key participants [23], and TMO [24]. However, these topics have not been sufficiently investigated in construction projects that use the 3D printing technology, which is attributed to the novelty of this technology. In addition, organisational structure of construction projects that use the 3D printing technology has not been thoroughly investigated [17, 18]. This review study confirms that organisational structure of projects and 3D printing construction projects must be connected appropriately. Moreover, the laws and regulations of each country have defined and classified the roles and responsibilities of key participants in construction projects, and they have been confirmed and/or supplemented by professional norms and standards, both in the selected countries and globally. However, we did not find novelty in such regulations or standards caused by the emergence of 3D printing. Nevertheless, this is primarily the case with conventional construction technologies, where new and alternative technologies, including 3D printing, have been largely neglected. In addition, all processes of the 3D printing technology have been attempted to be standardised by drawing parallels with conventional construction.

Therefore, in this study, within the first part, during the systematization of the literature review, associated conclusions, and possible bases for defining the organisational structure of construction projects using the 3D printing technology could be derived and adapted from, above all, previous research in conventional construction, but also studies from other industries.

5.2. Case study 1: 3D printed formwork for stairs - Leipzig, Germany

The first case study analysed the 3D printing of staircase formwork within the construction of new bank buildings in Leipzig. It was basically a curved arch of the foyer staircase and single-shell formwork masonry (monolithic construction). Because of the complexity of the project, it was perfectly suited for the integration of 3D printed formwork, where high-precision formwork was required to provide the staircase with a smooth and even curve. Moreover, 3D printing was a reasonable candidate because the conventional production of such a formwork owing to the triple curvatures in the design of the staircase could be incredibly expensive. The casting results were satisfactory such that there was no discernible difference between conventional and printed formwork inserts. In general, the use of 3D printing technology in the project significantly saved cost and time. However, the triple curvature could not be conventionally mapped with this precision. In addition, printed formwork elements were weather resistant and can be exposed to wind and weather without changing their properties. The surface was scratch-resistant; thus, no deformation occurs during concrete casting/compaction.

As for the organisational structure of the project, it was concluded that 'the main part in the realisation of such projects would be divided between the concrete technologist in cooperation with the structural engineer and the printer operator/manufacturer. In addition, the boundary between 3D printing and conventional construction is defined by these three. The concrete technologist in terms of the performance of the material, the structural engineer in terms of the requirements/load-bearing capacities of the component to be printed, and the "printer" in terms of what he can realize in terms of construction logistics and machine technology. They form the core team.'

In terms of individual roles, the client invests in a building and, ultimately, 'his main interest remains in the economic creation of the product and the added value that can be achieved with it.'

Moreover, the respondents stated that the project manager has less room for improvisation. 'There are clearly defined procedures that require more complex preliminary planning. Also, planning during construction will no longer be possible. The architect will have to do more research in advance from just designing and drafting. The degree of advance planning will increase significantly. This result must stand (incl. feasibilities) before the tender will be put out to tender. The more expertise about feasibility and state of the art in designs must be included.'

Structural engineers will still have to verify its stability. However, according to the replies, 'he/she will need precise values from the concrete technologist and will not be able to refer to standard values in the same way. He/she will possibly determine necessary bed strength values, which the concrete technologist must achieve in the formulation of the additives.'

The lessons learned confirmed that 'logistics and construction operations will be significantly impacted. The supply and traffic areas in connection with the different components, i.e., what will be printed and what will be built conventionally, will require more planning of construction operations and construction processes. In respect of construction operations, the printer will affect conventional construction processes, blocking traffic routes of its own material supply needs, etc. Therefore, it will be more difficult to change processes. Consequently, the importance of project supervision is much greater than in conventional construction.'

The experts agreed that 'there are two areas of additive manufacturing that are relevant to the contractor, the printing of structures (3D printing of concrete or similar masses) and the printing of construction aids and prefabricated parts. It is assessed that the contractor must significantly expand his knowledge and area of expertise or buy this knowledge externally. He will become more of a machine operator and will perform partial tasks in addition (installation of lintels, etc.).

The classic construction process in connection with site logistics will be completely different. An essential aspect will be that the times must be differentiated into printing times and manual rework. Printing times, for example, can run with an operator at night, while the necessary rework is carried out during the day. Also, there are no longer any limits to what can be built as far as the design of geometries is concerned. It is just that the expertise passes from the person doing the work to the designer, who constructs the precast parts in 3D. Various craftsmanship skills are therefore no longer important to the same extent.'

Finally, important feedback indicated that 'the qualification of manpower is changing from skilled construction worker / fitter to machine operator / service mechanic. Subsequently, the costs will shift from manpower construction to suppliers and project management.'

5.3. Case study 2: Manufacturing wall sections – United KingdomK

The second case study analysed the wall sections to be assembled into a residential structure. Moreover, 3D printing was chosen to achieve the goal of creating free-form and low-cost shapes without moulds. This choice suggests advantages of the 3D printing technology by mass customisation of building structures, that is, topology-optimised structures. Free-form, low-cost, and material-efficiency were detected as the biggest strengths, and surface finish, early investment in high-end equipment, and the need for specialists (operators) were the biggest weaknesses of using the 3D printing technology. The results of this case study showed that 'a good project team should consist of specialists from difference backgrounds including material, structural engineering, CAD/CAM/robotics, mechanical and manufacturing engineering, building service, construction management, etc.' For the client, it could mean 'less sub-contractors and easier to manage a project as a 3D printing company is likely to fulfil all the work.' The respondents believe that 'the role of project manager depends on two different conditions, in-situ on-site printing project where it will be more about managing machines and equipment than managing people and offsite printing + on-site assembly where more focusing on supply chain and logistics will be needed.' The main difference of the architect role is 'Design for Manufacturing/Printing.' The architects can actually 'dominate a whole project as his/her design should already consider the implementation of the printing process, or rather, architects is part of a manufacturer/constructor.' In role of the structural engineer 'there would probably be no difference.' In any case, it is necessary to fulfil all requirements for the mechanical resistance and stability of the construction. More managing machines and equipment than managing people and focusing more on supply chain and logistics will be reflected in project control tasks. The role of the main contractor 'will not change much - it will still be project construction and management of the construction. But its job content may change regarding the engagement of 3DP methods, e.g., sub-contracting to a 3DP company or getting (buying/renting) equipment or service from a professional 3DP company to conduct the work.'" Consequently, 'it accelerates the transformation of the profession and /or occupation of the workers on the construction site, with higher cost in the project team but lower cost in manpower and suppliers.'

5.4. Case study 3: Residential Building - Arizona, United States

The third case study analysed the exterior and interior walls of an upcoming residential house. The company that delivered and maintained the 3D printer came from Denmark; thus, both the standard and practices were acquired from similar projects completed in Europe. A gap not only in the creation of CAD files but also in all other segments between the new technology and existing paradigm was noticed, which prevented the desired success of the project. The project was designed as a client experiment with a desire for automation as a potential solution to the lack of skilled labour in the market. Nevertheless, it was concluded that 'the current level of automation does not correspond to the desired one and that the dependence on human intervention is still too high. It is also inferred that research and development in all directions and all aspects is needed (software, materials, hardware, etc.).' According to the experience, 'there are fewer and fewer "serviceable" people on the construction site, both in the labour and management roles and aspects. Without the means of automation, the housing shortage will become an unmanageable problem. The solution to this problem is the future potential of 3D printing technology.'

The main challenge was 'to think outside the box, owing to classic example of new technology and existing / old paradigms which followed in a weaker-than-expected result.' However, 3D printing could offer a solution for any unique/complex concrete form that would require one-off/custom formwork and should consider printed concrete as an alternative, as presented in this case study. Owing to the details of each project and lack of reference examples, general conclusions as to an ideal project team is difficult.

The difference in terms of the investor is that 'in this case the investor must buy / rent a 3D printer, which is, logically, the most important item of such a project.' However, this case was not a project for profit; thus, its goal differed from that of conventional construction projects. In general, the task of project manager 'is to coordinate, only in this case, additionally, to coordinate aspects of technology that some subcontractors have probably never seen before. Also, almost every participating company on this construction site has its own project manager and therefore it was concluded that is difficult to generalize their role.'

The architect 'must be aware of the printer's capabilities and apply it to his rendering to become a reality. Not every axis can be printed exactly according to our imagination / design. Therefore, in this case, the architect must be aware of the physical limitations of 3D printers right from the start.'

Currently, 'there is no difference in how a structural engineer treats a 3D printed house compared to a conventional construction house since all projects always require some kind of conventional structural measurement,' that is, vertical load, column load-bearing capacity calculation, etc. Therefore, structural engineers do not consider the structural capability of printed walls because it only serves as a "formwork" for everything else in this case. However, this "formwork" must fulfil all technical requirements, and concrete in the conventional formwork together with reinforcement. However, 'the role should be adapted and there should be some new way to test structural integrity and just basic cylinder testing that structural engineers are doing normally is simply not sufficient.' In this case, many paradigm shifts in basic assumptions exist that have not occurred.

There was 'no special difference spotted in role of the quantity surveyor.' In addition, all other observed risks, precautions, and methods should be considered.

'In most respects the role of the contractor is similar to that of the project manager.' This is a specific and unique structure for which the contractor, regardless of general experience, probably has no reference knowledge. The full potential of 3D printing has not been sufficiently defined or realised; thus, what will happen with the necessity for manpower is hypothetical. The tendency is to automate the process; however, it is highly distant from practical applications. 'It is also impossible to get an accurate picture of the costs because companies in such cases are still struggling to find investors.' Furthermore, many volunteers and workers worked free of charge, which spoils the real picture of costs according to the scale that would be used in a conventional construction site. In summary, there are 'no exact costs for a 3D printed house because there is no possibility to buy one at a specified price from a company according to the standard procedure, they are always part of a one-time experiment.' In addition, selling or buying one price is always considerably higher than that of the conventional construction project in the range of 30–40%.

6. Conclusions

First, the question of what has been identified as to the roles, responsibilities, and interactions of the key participants in construction projects using the 3D printing technology is answered. The latest advancements in additive manufacturing technologies suggest that large-scale 3D printing systems have a considerable capacity for delivering completely automated construction projects [34]. Nonetheless, our investigation suggested that studies on the influence of 3D printing technology on the roles and responsibilities in the organisational structure of construction projects are lacking. The literature review revealed that a specific topic is still a dark spot. Practitioners working on 3D pilot projects are gathering first findings, which confirm the necessity of parallel development of management and organisation along the new technology. This study suggests that many studies must be conducted on these topics in the future, as new technologies require a new organisational paradigm, or at least aligning or adjusting the existing one. This study provides significant insights into three different case studies. The use of printers and possible transfer of part of the production to the plant will positively affect the construction industry, which is facing a shortage of construction workers. However, this will shift part of the costs from manpower construction to suppliers and project management. Novelty is the appearance of a 3D printing party, either internal or external, and enlarging the project team by new specialisations. Moreover, architects and project managers will be highly affected owing to changes in the production process, team staffing, and organisation.

The second question considered the roles, responsibilities, and interactions of key participants in projects using the 3D printing technology compared to those of conventional construction projects. Key project participants were considered the same as those of the conventional construction project. The results confirmed that selected roles, including the client, project manager, quantity surveyor, structural engineer, and contractor, are significant in projects using the new technology. However, it is expected that the new technology will influence their jobs, responsibilities, and competencies. The case studies indicated that the major effect of the new technology would be on the design, supply chain, and quality; thus, responsibilities and processes of the integration, scope, procurement, risk, and stakeholder management must be aligned.

In addition, the new technology might positively affect famous "iron triangle" represented by time, cost, and quality. Furthermore, the effect will all above have on HRM in projects, potentially the key area influenced, owing to the reality that specific people and their competences are always behind any human activity and results. Moving part of the activities from construction sites to industrial facilities will positively affect the shortage of construction workers, particularly in developed countries.

The results confirmed that clients/investors will stay focused on project business cases and value creation, and the new technology will be embraced with reasonable support. The role of architect will be challenged by a more difficult process of potential later changes in design. In addition, an architect will have to cooperate even more closely with other specialists, such as concrete technologists and structural engineers. It might be predicted that "a certain quartet" formed by architect, technologist, structural engineer, and printer operator/manufacturer might form a sub-team beginning from the design process. Quantity surveyor/site supervisor jobs might significantly change because of shifts closer to off-site production. In particular, it significantly affects contractors as they will be faced with a dilemma either to produce or subcontract to buy printing machines. Nevertheless, a contractor or supplier will need to gain new knowledge and competencies and introduce machine operator jobs. In general, the 3D printing technology will cause new reality with less people and more skills, which will extensively influence the project manager. Usually, a project manager takes on a coordination role, driven by expectations and realities, and framed by participants and processes. We believe that within such a framework, the complexity of the job will rise, despite less on-site work force. Processes will change and the participant group will enlarge with new specialists and claim new interactions between on- and off-site parallel activities. The pressure on management "iron triangle" delivery criteria will increase because of expectations from the new technology. That must be exactly managed by a more efficient and effective organisation in the project, which must be tailored for a combination of on-site and industrial production.

The third question examined the necessity of adapting the existing project management methods/project organisational structure to the new technology. Obviously, future improvements of the 3D printing technology will be based on the quality control of products, including rheological control of materials, geometric and dimensional conformity, and structural performance, to achieve mass customisation with predictable quality to guarantee the geometry and dimension of each component to be within tolerance and achieve the whole assembly. Moreover, the new technology will yield verified advantages and gains. While clients/investors will primarily focus on the effect on value to be created and financial details, contractors will concentrate on the supply chain and delivery processes, while management professionals will be faced with new challenges, particularly within the integration, scope, risk, and stakeholder management fields. Furthermore, the competence model and updates for all key roles in the preparation and construction processes must be completely considered. Therefore, project management methodologies in the construction industry will require new adaptation and upgrades; thus, we encourage future studies on these suggested sub-topics.

Finally, the key question is: "Which of the findings in this study is the most urgent and important aspect to be studied"? Obviously, the organisation and management must follow the development of new technologies. We believe that, at this stage, the architect and project manager must comprehend the benefits of 3D printing, include new specialists in the project team, and model processes and relationships to contribute to the success of the construction project. Consequently, project stakeholders and community can leverage new technologies.

This study primarily assumed that 3D printing was an emerging trend that would be embraced by the construction industry and yield expected benefits to stakeholders; the benefits would be particularly more efficient and effective work, where more value will be created. The limitations of this study stem from the fact that only three cases were investigated, where 3D printing was implemented similar to the pilot cases.

Acknowledgements

The authors would like to thank Mr. Tobias King (Director Marketing & Applications - voxeljet AG), Mr. Helmut Hilliges (Senior Project Technician - Doka GmbH) and Mr. Jarett T. Gross (Construction Tech Journalist - Automate Construction) who participated in the design, planning, and execution of the case studies.

REFERENCES

[1] Berman, B.: 3-D printing: The new industrial revolution, Business Horizons, Elsevier, 55 (2012), 2, pp. 155–162, https://doi.org/10.1016/j.bushor.2011.11.003

[2] Khajavi, S.H., Partanen, J., Holmström, J.: Additive manufacturing in the spare parts supply chain, Computers in Industry, Elsevier, 65 (2014), 1, pp. 50–63, https://doi.org/10.1016/j.compind.2013.07.008

[3] Labonnote, N., Rønnquist, A., Manum, B., Rüther, P.: Additive construction: State-of-the-art, challenges and opportunities, Automation in Construction, Elsevier, 72 (2016), 3, pp. 347–366, https://doi.org/10.1016/j.autcon.2016.08.026

[4] Walter, M., Holmström, J., Tuomi, H., Yrjölä, H.: Rapid manufacturing and its impact on supply chain management, Proceedings of the Logistics Research Network Annual Conference, Dublin, pp. 9–10, 2004.

[5] Gebler, M., Uiterkamp, A.J.M.S., Visser, C.: A global sustainability perspective on 3D printing technologies, Energy Policy, Elsevier, 74 (2014), issue C, pp. 158–167, https://doi.org/10.1016/j.enpol.2014.08.033

[6] Ghaffar, S.H., Corker, J., Fan, M.: Additive manufacturing technology and its implementation in construction as an eco-innovative solution, Automation in Construction, Elsevier, 93 (2018), September 2018, pp. 1–11, https://doi.org/10.1016/j.autcon.2018.05.005

[7] Wu, P., Wang, J., Wang, X.: A critical review of the use of 3-D printing in the construction industry, Automation in Construction, Elsevier, 68 (2016), August 2016, pp. 21–31, https://doi.org/10.1016/j.autcon.2016.04.005

[8] Yeh, C.C., Chen, Y.F.: Critical success factors for adoption of 3D printing, Technological Forecasting and Social Change, Elsevier, 132 (2018), issue C, pp. 209–216, https://doi.org/10.1016/j.techfore.2018.02.003

[9] Spicek, N.: Building regulation for 3D printing in construction - Case study legislation for a 3D printed house - Project "Cabana", 8th Scientific Conference with International Participation - All about people, Maribor, pp. 66–78, 2020.

[10] Radujkovic, M., Sjekavica, M.: Project Management Success Factors, Procedia Engineering, 196 (2017), pp. 607-615, https://doi.org/10.1016/j.proeng.2017.08.048

[11] Guhathakurta S., Yates J.: International Labour Productivity, Journal of Cost Engineering, 35 (1993) 1, pp. 15–25.

[12] McTague, B., Jergeas, G.: Productivity improvement on Alberta major Construction projects, Phase I-Back to Basics, Construction Productivity Improvement Report, Project Evaluation Tool, Alberta Economic Development Board, May 2002.

[13] Soham, M., Rajiv, B.: Critical factors affecting labour productivity in construction projects: Case study of South Gujarat Region of India, International Journal of Engineering and Advanced Technology (IJEAT), ISSN: 2249, 8958, 2 (2013) 4, pp. 35–40

[14] Yuan, H.: Critical management measures contributing to construction waste management: Evidence from construction projects in China, Project Management Journal, 44 (2013) 4, https://doi.org/10.1002/pmj.21349

[15] Parasuraman, A.: Technology readiness index (TRI) a multiple-item scale to measure readiness to embrace new technologies, Journal of Service Research, Sage Publications Sage CA: Thousand Oaks, CA, 2 (2000) 4, pp. 307–320, https://doi.org/10.1177/109467050024001

[16] Lee, Y., Kozar, K., Larsen, K.: The Technology Acceptance Model: Past, Present, and Future, Communications of the Association for Information systems, (2003) 12, pp-pp, https://doi.org/10.17705/1CAIS.01250.

[17] ISO 21502:2020(E) - International Standard: Project, programme, and portfolio management - Guidance on project Management, INTERNATIONAL STANDARD (2020), First edition.

[18] European Commission Centre of Excellence in Project Management (CoEPM²): PM² Project Management Methodology Guide 3.0, Publications Office of The European Union, (2018), Luxembourg.

[19] Chen, C-J., Huang, J-W., Hsiao, Y-C.: Knowledge management and innovativeness: The role of organizational climate and structure, International Journal of Manpower, 31 (2010) 8, pp. 848–870, https://doi.org/10.1108/01437721011088548

[20] Besklubova, S., Skibniewski, M.J., Zhang, X.: Factors affecting 3D printing technology adaptation in construction, Journal of Construction Engineering and Management, 147 (2021), 5.

[21] Mellor, S., Hao, L., Zhang, D.: Additive manufacturing: A framework for implementation, International Journal of Production Economics, Elsevier, 149 (2014), issue C, pp. 194–201, https://doi.org/10.1016/j.ijpe.2013.07.008

[22] Sonar, H., Khanzode, V., Akarte, M.: Investigating additive manufacturing implementation factors using integrated ISM-MICMAC approach, Rapid Prototyping Journal (2020), ISSN: 1355-2546, pp. 1837–1851, https://doi.org/10.1108/RPJ-02-2020-0038

[23] Deep, S., Gajendran, T. & Jefferies, M.: A systematic review of 'enablers of collaboration' among the participants in construction projects. International Journal of Construction Management, 21 (2019) 9, pp. 919–931, https://doi.org/10.1080/15623599.2019.1596624

[24] Fellows, R., Liu, A.: Impact of participants' values on construction sustainability, Engineering Sustainability, ISSN 1478-4629, E-ISSN 1751-7680, 161 (2008) 4, pp. 219–227, https://doi.org/10.1680/ensu.2008.161.4.219

[25] Wirth, A., Würfele, F., Broocks, S.: Rechtsgrundlagen des Architekten und Ingenieurs, 2004. Edition, Vieweg+Teubner Verlag, 2004.

[26] CDM: The Construction (Design and Management) Regulations 2015, Construction (Design and Management), Regulations 2015, legislation.gov.uk, https://www.legislation.gov.uk/uksi/2015/51/contents/made, 10.04.2022.

[27] DLA piper: General construction law, https://www.dlapiperrealworld.com/law/index.html?t=construction&s=legal-framework&c=US, 14.04.2022.

[28] Budde, N.: Construction law: What contractors, subs, and suppliers must know, LevelSet, https://www.levelset.com/blog/construction-law/, 10.04.2022.

[29] Caravella, J.: Understanding roles and relationships of construction project participants. Who does what? AIA contract document workshop, https://www.liconstructionlaw.com/construction/understanding-roles-relationships-construction-project-participants1/, 12.04.2022.

[30] Adamu, M.: Quantity Surveyor's Role in Public-Private Partnership Highway Concession, International Journal of Engineering Research & Technology (IJERT), ISSN (Online):2278-0181, 5 (2016) 2, https://doi.org/10.17577/IJERTV5IS020408

[31] Voxeljet: Mit 3D-Druck effizienter zur komplexen Betonschalung, https://www.voxeljet.de/case-studies/architektur/mit-3d-druck-effizienter-zur-komplexen-betonschalung/, 08.01.2022.

[32] Perrot, A., Rangeard, D., Nerella, V.N., Mechtcherine, V.: Extrusion of cement-based materials - an overview, Rilem Technical Letters, 3 (2018), https://doi.org/10.21809/rilemtechlett.2018.75

[33] Kuchinskas, S.: Habitat for humanity builds faster and cheaper by 3D printing affordable homes, Redshift by Autodesk (2021), https://redshift.autodesk.com/articles/3d-printing-affordable-homes, Photos: Courtesy of Peri/3D Construction Inc, 14.04.2022.

[34] Halicioglu, F.H., Koralay, S.: Applicability analysis of additive manufacturing methods in construction projects, GRAĐEVINAR, 72 (2020) 4, pp. 335–379, https://doi.org/10.14256/JCE.2334.201

[35] Chun, K.W., Kim, H., Lee, K.: A Study on Research Trends of Technologies for Industry 4.0, 3D Printing, Artificial Intelligence, Big Data, Cloud Computing, and Internet of Things: MUE/FutureTech 2018, Advanced Multimedia and Ubiquitous Engineering, pp.397–403, (2018), https://doi.org/10.1007/978-981-13-1328-8_51