ITU A|Z • Vol 19 No 3 • November 2022 • 671-688

Determination of architectural construction technologies - detail design interaction with the expert opinion method in the context of 3D printing technologies

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Received: November 2021 • Final Acceptance: July 2022

Abstract
As construction technologies are taken into consideration in design processes, one of the factors determining the direction of the development of construction technologies is the actions within the detail design process. This mutual effect emerges as an architectural design-construction interaction. This study aimed at finding an answer to the question: "In the near future, when the newly developed 3D printing technology is used in a widespread manner as architectural construction technology, what effect will it have on the detail design process for architectural construction?". For this purpose, the "Delphi-Expert opinion method", which is a forecast method, was used in this study. With this method, questions were posed to selected academicians and architects, as experts who had different levels of experience, ranging from 2 to 50 years, in detail design, about the research question. As a remarkable result of using the Delphi method, regarding the use of 3D printing technology, they stated that joints and additional elements will almost disappear and the details will be "simplified" when compared to today. Finally, the results obtained using the Delphi method were applied to the details of the intersection area following the "research through design" and "prototyping" methods. With this study, the future use of 3D printing technology as a building technology was examined through the construction-design interaction and the possible effective development aspects of this technology were foreseen by experts. The applicability of the study results was demonstrated by transforming these predictions into new design sub-processes and applying them to a sample.

Keywords
3d printing, Architectural detailing, Construction technology, Delphi study, Forecasting.

doi: 10.5505/itujfa.2022.91129

1. Introduction

Three-dimensional (3D) printing has great potential in the construction industry as a technology that can create complex geometries without the high cost of manual labour or temporary supports, and can significantly reduce construction time. Moreover, the use of emergent technology will probably cause changes in the design methods that are used today.

1.1. Subject and context

In this section, 3D printing technology and the architectural detail design process are examined by taking into consideration the interrelation between them.

1.1.1. Digital technologies and 3D printing

Digital production technologies have been used as a construction technology in different areas since the beginning of the 21st Century. There are mainly 4 types of digital production technologies, which comprise subtractive, formative, assembly, and additive (Naboni & Paoletti (2015), Hauschild et al. (2011), Redwood et al. (2017), Kolarevic (2003). 3D printing technology is one of the additive manufacturing technologies. According to Kolarevic (2003), 3D printing technology is the act of producing parts by adding continuous layers of material onto each other.

Woensel et al. (2018) compiled 3D printing methods used as architectural construction technology according to their features, such as process properties, manufactured materials, applications in the building industry, build volume, and printing speed. There are 15 architectural printing methods which can be classified with process properties as follows:

- Extrusion: Contour Crafting, Concrete Printing, Cellular Fabrication, 3D Foam Printing, Fused Deposit Modelling, Freeze-Form Extrusion Fabrication
- Binder Jetting: D-Shape, Three-Dimensional Printing
- Vat Photopolymerization: Stereolithography
- Material Jetting: Multi-Jet Modelling
- Sheet Lamination: Laminated Object Manufacturing
- Powder bed fusion: Selective Laser Sintering, Selective Laser Melting, Electron Beam Melting
- Directed Energy Deposition: Laser Metal Deposition

In these architectural printing methods, shelter, housing, wall, facade panel, decorative element, structural element, and intersection element applications are performed via the use of concrete, ceramic, polymer, polyurethane foam, glass, wood, and metal. The production volume for these varies between approximately 1 and 2500 m^3, with a printing speed between 10 and 250 mm/s.

The main advantages of using 3D printing technology as an architectural technology include reducing the volume of labour used and number of injuries (Wu et al, 2016), reducing the construction time (Keating et al., 2017), increasing the controllability (Hager et al., 2016), enabling the production of complex shapes at building scale (Yossef & Chen, 2015), facilitating rapid prototyping (Kocovic, 2017), using only as much material as the object requires (Wu et al., 2016), expecting more function from a single building element (Sarakinioti et al., 2018) and using it during extreme climatic conditions or post-disaster production (Keating et al., 2017).

Also, the main disadvantages of the technology include high initial investment cost (Yossef & Chen, 2015), the problems about the integration of electrical and plumbing systems (Wu et al., 2016), the difficulties in construction of large surfaces (Craveiroa et al., 2019), and the unemployment problem that may occur since it will require less labor than traditional construction methods. Here, the construction sector stakeholders should transform the workforce to a new arising safer area by replacing the construction with manpower, where the workers' injury potential is high, with the machine.

1.1.2. 3D printing technology and architectural design interaction

3D printing technology affects certain aspects of design, such as form, integration, and customization. As construction technologies are considered in design processes, one of the factors that determines the direction of the development of construction technologies is actions in the design processes. This mutual effect emerges as an architectural design–construction interaction. The effect of construction technologies on design has been examined from different aspects, as follows:

• The impact of industrialization on design: Standardization, mass production, rationalization, modulation, size tolerance, and transportation and assembly convenience (Staib et al.,2008) and (Caneparo, 2014).

• The use of prototypes as a design tool with industrialization (Anderson, 2007).

• The effect of open industrialization on design (Şener, 1986).

• Integrated design and construction process when using technology that has a dominant influence on the design (Smith, 2010).

• Monolithic construction with fewer joints (Smith, 2010).

Design for manufacturing and assembly (DfMA), which is used in engineering and industrial design to eliminate manufacturing difficulties and minimise manufacturing, assembly, and logistics costs, is also preferred for construction with the increase of digital manufacturing and prefabrication. In addition to these, the capabilities of additive manufacturing technologies provide an opportunity to rethink DfMA and take advantage of the capabilities of these technologies (Gibson et al., 2015). Building designer stakeholders have begun to develop DfMA guides and evaluation metrics, which can be used in architectural design (Shang, et al., 2020). Tan (et al., 2020) offered the cross-sectoral learning of DfMA from manufacturing to construction, with principles from 5 fundamental aspects, which comprise contextual basis, technology rationalization, logistics optimization, component integration, and material-lightening, either individually or collectively.

The necessity to consider the construction process of the design undoubtedly maintains its importance from the very beginning of the design process. However, the detailing process, which makes the conceptual design ready for the construction, must be able to transfer the characteristic and aesthetic decisions taken in the pre-design to the construction stage, with a high level of creativity (Emmitt, 2007). This detailing process can be called the architectural detail design process for construction. The design methods used in this process, compiled from the literature, depending on whether they are for typical or intersection area details consist of the following:

• Typical area detail design methods: A building element is named as “typical area detail” with its parts in its continuity (Altun & Türkay, 2015). The methods are: Müller (1990), Aygün (et al., 1999), and Altun & Türkay (2015).

• Intersection area detail design methods: The intersection points where different building elements and other building systems come together are called “intersection area details” (Altun & Türkay, 2015). The method is: Emmitt (et al., 2014).

• Methods for designing both typical and intersection area details are: Allen (2016) and Rich & Dean (1999).

Thus, design processes also differ in relation to the changes in construction technologies. The concept of “build virtually, rather than build actually” has been the keyword of the research and process developments for the construction industry of the 2000s (Newton et al., 2009). Gao and Fischer (2008), determined the usage areas of virtual construction made with 3D models, such as to determine the needs of the user, interact with non-professional stakeholders, analyse design options, control different system mappings and constructability issues, manage supply chains, and make construction planning.

1.2. Research question, purpose and scope

Within the framework of the abovementioned topics, this study aimed at finding an answer to the question: “In the near future, when the newly developed 3D printing technology is used in a widespread manner as architectural construction technology, what effect will it have on the detail design process for architectural construction?”. The general aim of this study, in line with the research question, was to determine the effect of the change in architectural construction technology on the design process in the "construction–design" interaction. The focus of the study was to develop a prediction about the effect of 3D printing as architectural construction technology on the detail design process for architectural construction. Accordingly, the sub-objectives can be listed as follows:

- Realizing the design process example for 3D printing technology,
- Using the future-oriented forecast method in a research in the field of architecture,
- Creating data about emerging technologies and detail designs for future architectural technology education,
- Guiding the construction sector toward studies on this subject, and
- Providing information that facilitates adaptation to developing technologies for architectural offices by presenting the advantages of 3D printing technology and the work that is currently being conducted.

2. Method and process of research

In this study, three methods were used respectively: "literature review, analysis and compilation", "Delphi-expert opinion method", and "research through design and prototyping". Methods are explained in Figure 1 and one by one below (Artuğ, 2020).

2.1. Literature review, analysis and compilation

Within the framework of the scope; The literature review and analysis were made on architectural construction technologies, detail design for architectural construction, architectural design-construction interaction, construction technology analysis and comparison criteria, and intersection area details subjects in the "Istanbul Technical University Library, YÖK-Thesis, Proquest Dissertations & Theses Global, EthOS, TU Berlin, TU Münich, Universitaet Stuttgart, NARCIS, TU Delft, TU Eindhoven" national and international databases, and "academic book, MSc/PhD thesis, article, paper" resource types. The information was compiled by determining the titles again achieved from literature.

Architectural construction technologies; literature search was conducted, and 50 sources closely related to the subject reached were added to the sources to be examined. Construction technologies were classified considering the "historical development framework" of Eser (1977) and types of resources as "technologies up to the first quarter of the 21st Century" and "digital production technologies". Resources about 3D printing, one of the digital production technologies, were discussed in more detail.

For the detail design for architec-

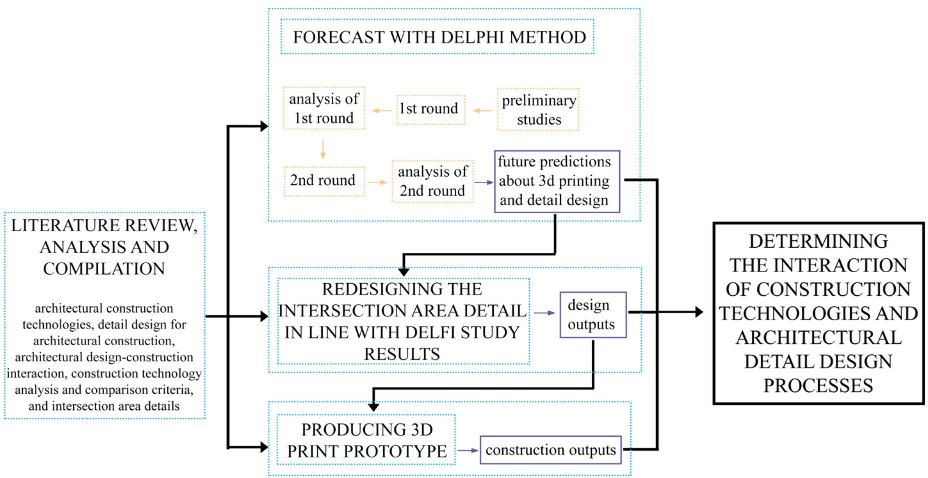

Figure 1. *Flow chart.*

tural construction, as discussed in Kızılyaprak & Altun (2011), six different sources were selected that describe the detail design processes based on the method of "systematically defining the steps expected from the user and guiding the designer". These resources were analyzed by examining the usage purposes and methods of the processes and the examples of the applied processes.

About the architectural detail design-construction interaction; sources that deal with "expectations of production technologies from design outputs" (Rosen, 1998) and "the effect of possibilities and limitations of production technologies on the design process" (Emmitt, 2012) were examined from different sides and classified according to how they see the "design-construction" interaction.

For the construction technology analysis and comparison criteria, Özkan (1976), Emmitt and Gorse (2014), Smith (2010) and Eser (1982) sources were analyzed "by considering the way they were taken in the context of the comparison criteria". The criteria reached were classified according to the topics they addressed; a total of seven criteria were classified based on group titles and were made into a set of criteria by clearing repetitions.

Future-oriented forecast methods; literature search was conducted and 15 sources related to technological forecasts were analyzed in detail and in order to determine the forecast method; Porter et al. (2011), Jantsch (1967), Mishra et al. (2002), Kang et al. (2013), Türkmenoğlu (2017), Landeta et al. (2011) sources were selected.

2.2. Forecasting with Delphi-Expert opinion method

Mishra (2002) indicates that in a rapidly developing and transforming field such as technology, being able to develop "future-oriented prediction (forecast)" also offers the opportunity to prepare the necessary infrastructure for this development to progress smoothly. The forecasts can be directed to changes in the use of existing technologies and new technologies that will emerge in the long term.

2.2.1. Analysis of forecast methods and selection of Delphi method

Method selection was made between forecasting methods classified in selected sources in the 2.1 section, such as "monitoring, expert opinion, trend analysis, scenarios, brainstorming, utopia, Delphi technique, etc." The criteria, such as "forecasting processes, scales, areas of use, usability in forecasting about construction, data requirement levels, resource requirements, and the level of knowledge that experts should have" were used while making method selection. Prediction method selection schemes found in Armstrong (2001) and Sharma (2018) were another data taken into account when making a selection. Finally, the "Delphi" method was chosen to be applied, considering all these selection schemes and the time scope characteristics of the study (Artuğ, 2020).

2.2.2. Delphi method

Weber and Ladkin (2003) define the Delphi data collection technique as a design-inspired foresight project in which uncertainty over factors that may affect an organization or industry can be freely discussed without fear of the reaction of relevant experts (Buhring & Koskinen, as cited in 2008). According to Woudenberg (1991) and Dalkey (1969), the Delphi method has three critical features. These are anonymity, controlled feedback, and iteration.

According to Mishra et al. (2002), the advantages of using Delphi as a forecasting method are; being reliable and accurate, having high flexibility because experts can easily change their estimates, being relatively simple and cost-effective, and being able to use in cases where historical data are limited.

2.2.3. Delphi method used in this study

In this study, scenarios for the future when the development and usage of the technology are uncertain were created, and the Delphi study was carried out by accepting this scenario as reality. Scenario planning techniques are helpful in times characterized by uncertainty, innovation and change. The "continued growth" scenario type was chosen, considering the development speed of the technology, and it was accepted that 3D printing technology would develop rapidly and its use would become widespread in the future (Amer et al. 2013).

Expert and round decisions

Many variations of the Delphi method have been used over the years. In studies, the number of rounds varies between 2-10 (Woudenberg, 1991). If the aim is to see differences of opinion, less than three rounds are sufficient to reach theoretical saturation or reveal sufficient information. For example, 41 doctoral theses made between 1981 and 2006, which used the Delphi method, applied 7 with two rounds, 29 with three rounds, 4 with four rounds, and 1 with five rounds. Although the number of experts in these theses varies between 8 to 345, and the average number of experts is 42 (Skulmoski et al., 2007).

According to Dalkey (1969), while the rate of inaccuracy decreases rapidly as the number increases, however, this effect decreases after 29 experts. Therefore, when the previous Delphi research samples were examined, it was decided to conduct this study in 2 rounds and with 30-40 experts, considering the time experts can spare and the aim of the emergence of different ideas rather than reaching a single absolute decision.

The process of this study is specified as two rounds by using the above mentioned sources related to Delphi and Skulmoski et al. (2007)'s article titled "Use of Delphi in postgraduate studies". In the first round of the Delphi method flow to be applied in this research study, as in the "Hybrid Delphi" method defined in Landeta (2011), a "focus group" study which is a group of 3-10 experts on the subject discusses for about an hour with the introduction questions given under the moderator management was deemed appropriate.

Selection of experts for Delphi method

The effect of the 'expertise' level consulted on the study's results is discussed from past to present. Ramadurai & Becattini (2013) specifies the level of expertise with the number of publications, years of experience, subject of expertise, membership to professional organizations, reputation and geographical coverage criteria. The traditional approach before the 2000s argues that only experts with high and intermediate levels of 'expertise' should be worked on. On the other hand, in recent years, it has been shared that the inclusion of experts from all levels is essential for different perspectives (Demirbaş & Polat (2010)). Considering these approaches, it was decided to seek the opinions of experts from different expertise levels in the study.

Preliminary studies

Since the subject is about new technology, there are no examples in the field of architecture in Turkey, and there is a limited number in the world, detailed preliminary information was prepared for the experts.

A pilot study was carried out to increase the level of understanding of the preliminary information, determine the duration of the interview and notice the problems that may occur in the process.

1st round - first meeting with experts

McKenna (1994) suggests that "personal touch" can help increase the rate of return (Keeney et al., as cited in 2011). For this reason, a face-to-face interview method was chosen to have a "personal touch" while making a preliminary information presentation and conduct the process in the form of a conversation between the researcher and the expert. After the preliminary information was given, the question set was presented to the expert, and the answers were recorded in writing and voice.

Analysis of 1st round answers, preparation of report and 2nd round questions

Scott and Black (1991) conclude that when the dissenting opinions are eliminated at the end of the first round, common ideas can be reached more easily without disrupting the broad scale of opinions (Keeney et al., as cited in 2011). For this reason, the first five answers with the highest number of answers given by at least two experts were transferred to the second round. According to Woudenberg (1991), statistical feedback can include the answer with the highest number of answers or all distributions. Therefore, only the percentage values of the answers transferred to the second round were reported regarding clarity.

If a sufficient consensus value was reached, which varies between 51% to 100%, the tour could be terminated at that stage (Keeney et al., 2011).

Analysis of 2nd round answers and the result of the work

The 2nd round answers received from the experts were compiled in tables for each question. Later, this information was transformed into a graphical representation, and the results were interpreted.

According to the Delphi study results, to determine the possible effects of the use of 3D printing technology in construction on the architectural design processes in detail, the sub-processes of the detailed design methods were discussed and associated with the results of the Delphi study.

2.3. Design scenario development with research through design method

Research through design is an approach that uses design practice as a legitimate method of inquiry and research (Herriott, 2019). This method aims to reach a design based on specific data defined by Frayling (1993). In this framework, the steps followed in the process and new and different experiences at these steps add to the design are reported. With this approach, it is ensured that the "theoretical" studies and the "practical" studies are linked together and the research results are applied on a design (Friberg, 2010). In this study, the research through design method was chosen to test the usability of the theoretical Delphi results in the practical detail design process (and to refine them if necessary) and to reveal the steps of the 3D printing detail design process. Furthermore, within the framework of research through design method; the intersection area detail selected in the 2.1. section has been redesigned according to 3D printing technology, in line with the results obtained from expert opinions (Artuğ, 2020).

2.3.1. Transforming Delphi results into design input

The results obtained in the Delphi forecast study have been accepted as a hypothetical reality, and each was transformed into a "design input". Based on these design inputs, the existing detail was redesigned step by step for 3D printing technology. Digital modelling was used as a design tool.

2.4. Detail prototyping with 3D printing

Prototyping is ubiquitous in developing innovative products, services, and systems. In the study of Camburn (2017), results prove that prototyping is critical, especially in exploring concepts rapidly in the early stages of design. Therefore, it was decided to use the prototyping method in this study based on the role that is "prototype as a research archetype", among the roles of prototyping in the design process, defined by Wensveen & Matthews (2014). Such prototypes, which stand as an archetype, elaborate a new perspective on "research through design".

The purpose of research prototypes used in research projects rather than product development is to explain and test concepts that answer questions from the theoretical literature or a research program (Koskinen & Frens, 2017). In addition to these purposes, a prototype was produced to test the constructability of the design and the general 3D printing rules on a sample production in this study.

"Taşkışla 102b Informatics Laboratory/Faculty of Architecture, Ultimaker3 Extended" 3D printer was used in this prototype production. The need for printing filaments was met with the "ITU BAP-Master's Thesis project support". As a result of the Delphi study, the model of the intersection area detail adapted to 3D printing technology was made ready for printing with preparation stages in Micallef (2015), printed in parts, and experimental production and assembly stages were observed (Artuğ, 2020).

3. Delphi study

In this section, respectively; the focus group was carried out, experts were selected, and briefing and questions were set for experts. Then 1st and 2nd rounds of the Delphi study and their reports were completed. Finally, the results of the second round were analyzed, the answers were evaluated, and the results of the Delphi study were obtained (Artuğ, 2020).

3.1. Focus group study

A focus group study was conducted with three experts under the moderation of the researcher in order to develop different perspectives on the subject and to contribute these inquiries to the Delphi study. The Focus group session started with the study's main question, "What are the effects of 3D printing on the detail design process when using 3D printing as an architectural construction technology?" and the participants were asked to express their opinions freely. The discussion, supported by keywords by the moderator, lasted about an hour. The different perspectives, such as the construction site process, the difference between being a robot/human in construction, and the performance requirement against environmental effects brought to the subject, were transformed into questions and added to the question series prepared in the continuation of the study.

3.2. Experts for Delphi method

The expert selection was made within the framework of the principles conveyed in the 2.2.3. section, as years of experience, architectural expertise areas, and membership to professional organizations. It was decided to conduct the study with 30 - 40 experts considering the previous research examples; 50 experts were contacted, and a total of 39 architects, including 20 academicians and 19 professionals from the construction sector, were included in the study as experts. The experts to be consulted in the study were selected following the criteria explained in section 2.2.3, such as the subject of expertise, geographical coverage, and years of experience:

a. Academicians

- Having a master's degree in building science and technology and working on the same subjects in the universities which are among the top success ranking of the architecture department in Istanbul (Istanbul Technical University, Mimar Sinan Fine Arts University, Yildiz Technical University, Gebze Technical University, Bilgi University, Ozyegin University).
- Having studies on architectural construction technologies and detail design.
- According to years of experience, five experts from 25 years and over, nine experts from 25 to 15 years, four experts from 15 to 5 years, two experts with 5 years and less experience.

b. Professionals from the construction sector

- Having graduated from the architecture department of the universities in Turkey.
- Having practical experience on detail design, and construction projects.
- According to years of experience, seven experts from 25 years and over, three experts from 25 to 15 years, six experts from 15 to 5 years, five experts with 5 years and less experience.

3.3. Briefing and questions for experts

In order to convey the workflow and 3D printing, the experts were informed about 10 minutes at the beginning of the 1st round. The content of this information is the purpose of the study, the definition of the Delphi method, the prediction process, the definition of 3D printing, the material catalogue of 3D printing used in architecture, the examples of 3D printed buildings, 3D printing design and printing process, 3D printing usage scenarios in architecture. For the subject to be understood and for the experts to adapt more quickly, three different scenarios have been developed for future 3D printing technology. In these assumption scenarios belonging to the years 2028, 2035, and 2058, the use of 3D printing technology and advanced materials at different rates in the production of the same detail is discussed. The 1/1 scale (20 x 20 cm) prototypes of the detail of these scenarios were printed with a 3D printer and presented to experts at the time of the interview. The detail of the scenarios was designed to be constructed in today's technologies; It is a ventilated external wall with a reinforced concrete core with rock wool as thermal insulation on the outside of the core and a terracotta tile cladding connected to the core with aluminium profiles. In the scenario of 2028, the reinforced concrete core and thermal insulation remain the same and are constructed on-site. However, the facade is produced as a panel with 3D printing technology as prefabricated. In the scenario of the year 2035, all layers are simultaneously produced in a single 3D printer with different material nozzles, using performance-enhanced materials, at one time and on-site. Finally, in 2050, it is produced by 3D printing on-site with an ideal material that can meet all performances without requiring layering. The sample presentation of these scenarios for 2035 is in Figure 2.

After the preliminary information, the "what will be the effects on the detail design process when using 3D printing as an architectural construction technology?" question was conveyed to the experts as the main problem of the study. In order to provide approaches to this problem and direct experts to think from various aspects, 21 design sub-processes and questions were prepared for experts. The design sub-processes and questions to which resources are given below can be seen in detail in Table 1.

- The criteria set which were created from the literature review by classifying used to analyze the construction technology (described in the 2.1. section),
- The focus group work which was conducted in order to develop different perspectives on and to contribute these inquiries to the Delphi study (described in the 3.1. section), and
- Detail design methods which were compiled from the literature (described in the 1.1. section).

3.4. Pilot study

A pilot study was conducted with two academicians and one professional expert to get feedback to determine the duration of the interview and to notice the problems that may be experienced

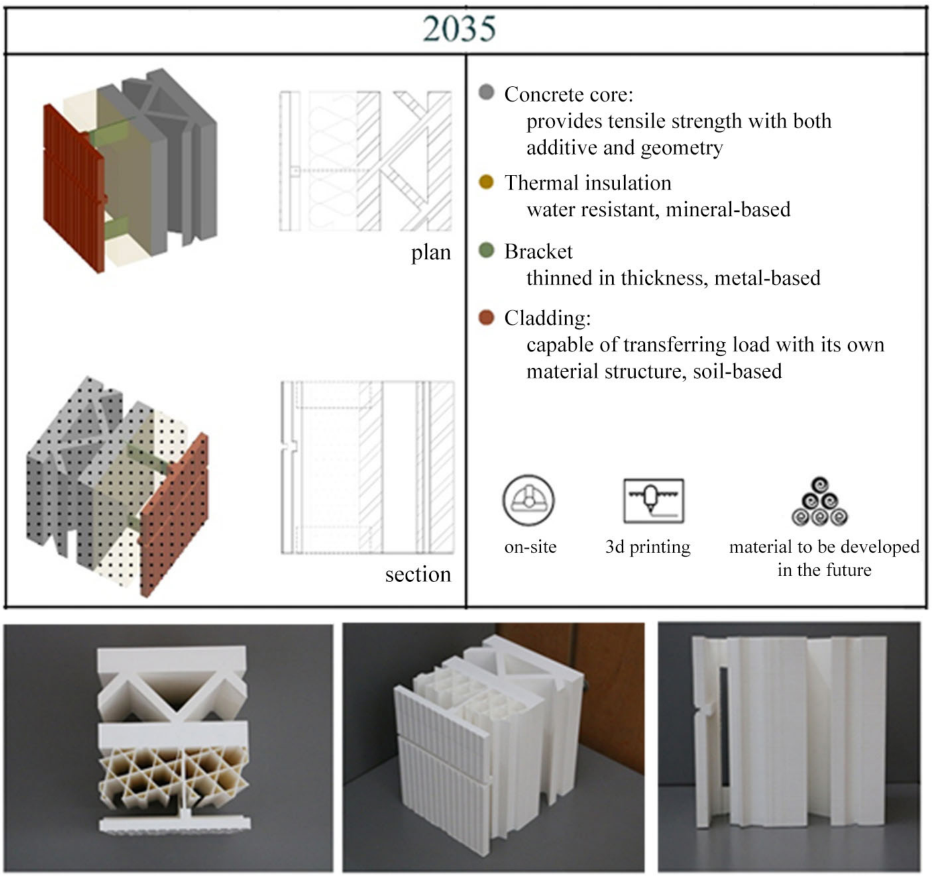

Figure 2. *Presentation of the future scenario for 2035: Section and plan drawing, technology setup and materials, and photographs of the prototype.*

Table 1. *(C1): design sub-processes and questions asked to experts, (C2): most popular answer at the end of the 2nd round, (C3): distribution of expert groups, (C4): re-design sub-process created from answers.*

(C1) **design sub-processes and questions asked to experts**		(C2) **Most popular answer at the end of the 2nd round**	(C3) **distribution of expert groups**	(C4) **re-design sub-process created from answers**
1. Do the criteria (ease of joint, tolerances, ease of quality control, logistic) we consider today when **deciding on the construction process (off-site / on-site)** remain valid for 3d printing technology? (criteria group - Özkan (1976) and Emmitt & Gorse (2014))	A	New criteria are added according to the material used and the capacity of the printer.	A 12 P 14 Σ 26	A multi-material printer that produces by material extrusion method was chosen. Thus, it can print more than one material at the same time.
	B	Quality control in 3d printing technology differs little depending on the construction process.	A 13 P 13 Σ 26	Since the quality control criteria loses its effect with 3d printing technology, it has not been taken into consideration in the construction process decision.
	C	On-site (atelier if necessary) construction will be more advantageous for this technology.	A 14 P 9 Σ 23	Since it is assumed to be constructed for once, not mass production, on-site construction was preferred.
2. Do the **construction stages need to be defined** in order to produce the desired detail for 3d printing technology? How do definitions change? (criteria group - Emmitt & Gorse (2014))		It is necessary at first but less definition need to be defined for the printer as the definition pools fill up, in the future.	A 9 P 8 Σ 17	The printing order is defined in the design output in terms of the starting point and priority for structure.
3. Is the **standardization needed for today's technologies** in line with the convenience and advantages it provides in the **construction process,** an enabling factor also for 3d printing? (criteria group - Emmitt & Gorse (2014))		Standardization is needed in line with the advantages provided by standardization and material strength.	A 10 P 10 Σ 20	Standardization has been observed when selecting element sizes and materials.
4. In the context of the construction process, should it be **defined in which order and in which direction the pieces will be joined**, and the detail should be developed by considering the 3d printing construction? (criteria group - Eser (1982))		It is necessary to design and define the joints considering the construction stages.	A 9 P 9 Σ 18	The joints of the materials within and between each other has been reduced as much as possible and how the existing ones will be joined has been defined.
5. "**Constructability on-site** " criteria (site conditions, workmanship, etc.) which are considering for today's technology replace "**printer constructability**"? (focus group)		"Printer constructability" becomes important, but "constructability on site" criteria still exist, even if a little.	A 15 P 15 Σ 30	Printer constructability; size, material used and formal limitations are taken into consideration.
6. Will **climate and environmental data** continue to be **design inputs** for 3d printing technology? Does the way the measures taken against the conditions (rain, sun, wind, etc.) change? (detail design methods)		Climate and environmental data continue to be considered as design inputs.	90% of the experts reached a consensus on the answer at the end of the 1st round.	Since the performances expected to be met in line with climate and environmental data preserved their existence, these data were taken into consideration in the design.
7. Does the importance of **a holistic process design** change with 3d printing technology when "decision making + design development + preparation for construction" is considered as a whole? (focus group)		As the design inputs are reduced, the process is shortened, but a process design is still needed.	A 10 P 12 Σ 22	A design and construction process design has been made.
8. Do the **design / aesthetic constraints** arising from today's technologies continue? how does it change? (criteria group - Emmitt & Gorse (2014))		The design boundaries are expanded but not completely destroyed.	84% of the experts reached a consensus on the answer at the end of the 1st round.	While making aesthetic decisions, it was thought more broadly than today, but the designer did not leave herself completely unlimited.
9. Are **design tools** such as digital model, physical model, sketch drawing continue to be used for 3d printing technology? How do the usage rates change? (criteria group - Emmitt & Gorse (2014))	A	Sketch drawing continues to be used as it is today.	A 13 P 16 Σ 29	Sketches were drawn during the design process.
	B	It is used more than today as model making will become easier with printing technology.	A 10 P 7 Σ 17	During the design process, 1/20, 1/5, 1/2 scale models were produced using a 3D printer.
10. Do the need to create **design options** continue in 3d printing technology as today? or the technology lead the designer to design the ideal from the very beginning? (detail design methods)		Creating design options is a design habit, it is not change with the technology.	A 10 P 10 Σ 20	The designer has designed without creating an option in line with her own habit
11. Is there any advantage in terms of criteria such as economy or time between the use of **details that have already been developed** and the details **specific to the project** in 3d printing technology? " (detail design methods)		3d printing technology encourages project-specific detail development.	A 14 P 16 Σ 30	Ready-made details are not used, details specific to the selected intersection area have been developed.
12. "Does 3d printing technology **encourage designers to create original designs** in the design process? **or does it restrict** it? " a.architectural design b.architectural detail design (criteria group - Emmitt & Gorse (2014))		It increases creativity in both scales for designers who are open to creative ideas.	A 6 P 9 Σ 15	The designer developed creative ideas by using the "search for the new" opportunity provided by technology.
13. When all other criteria (location, cost, time, technology, printer, material) are the same, what **level is the designer's intervention** when detailing the same concept project for 3d printing technology? (focus group)		Different designs continue to emerge.	A 14 P 12 Σ 26	The result, which argues that different designers will develop different detail solutions for the same concept project, was not used as a redesign sub-process in this detail design developed by a single designer.
14. Does **sorting the layers according to each other** keep its importance in 3d printing technology? (criteria group - Smith (2010))		There may be a decrease in layering, but order remains important and the designer decides as it is today.	A 14 P 13 Σ 27	The designer has decided on the order of the layers according to the performances.
15. Does it still require **preforming** so that the assembled parts are compatible with each other in 3d printing technology? (detail design methods)		If there is partial production, preform is required because it cannot form on-site.	84% of the experts reached a consensus on the answer at the end of the 1st round.	The print result is designed to be the final form, post-production finishing is not applied.
16. Does the requirement to use **additional parts** for a function to continue also need to 3d printing technology? (detail design methods)		Production-related errors are reduced and the components meet this requirement by geometrically differentiating within themselves, so the fittings are almost never used.	A 10 P 11 Σ 21	Since the additional parts are designed within the elements and formed by the freezing of the molten material while the joints are produced, no external addition was made.
17. Does the requirement to consider the **compatibility of the materials** with each other also need to 3d printing technology? (criteria group - Emmitt & Gorse (2014))		Even though technology brings solutions to some of the problems, compatibility should always be considered.	92% of the experts reached a consensus on the answer at the end of the 1st round.	The design has been made by taking into account features such as the compatibility between different materials and expansion differences.
18. Does 3d printing technology encourage the use of **complex materials**? (criteria group - Emmitt & Gorse (2014))		The development of technology causes the search for new materials.	86% of the experts reached a consensus on the answer at the end of the 1st round.	In today's conditions, it was not used in this design as there is no complex material that can be printed
19. Does the **integration of the systems** (service sys., structural sys., building element sys.) with each other maintain its importance in 3d printing technology? (criteria group - Emmitt & Gorse (2014))		Since it is a holistic design approach, integration becomes more important starting from the pre-design.	95% of the experts reached a consensus on the answer at the end of the 1st round.	Since the detail area does not include service systems, it is not used in this design as a redesign sub-process.
20. What would be the difference between presenting the final **design output** to **human / robot** for manufacture? (focus group)		It is necessary to define with a different language or format.	A 14 P 10 Σ 24	Necessary definitions have been made in accordance with the language of the printer.
21. Do different professions such as architect, civil engineer, mechanical engineer continue? or can the "**artificial intelligence**", design the building from beginning to end? (focus group)		Since a holistic design process will be required, an orientation towards "artificial intelligence". But the architect retains her/his role as designer and controller.	A 10 P 6 Σ 16	It was not used as a redesign sub-process due to the scope of this design.

years of experience						
	A = Academicians	A > 25	25 > A > 15	15 > A >5	A< 5	Σ = Toplam
	P = Professions	S > 25	25 > S > 15	15 > S >5	S< 5	

in the process. Based on the results, it was determined that the interview period needed to be approximately 45-60 minutes and increasing the number of 3D printing project examples in line with the purpose of the study.

3.5. Delphi study first round - first meeting with experts

Appointments were made with the experts, who were contacted via e-mail, and the offices and/or universities were visited for face-to-face interviews. Interviews were;

15 minutes inform + ~ 45 minutes (between 30 and 90 minutes) answering time

They lasted between 45-105 minutes. During the interviews, it was observed that the experts answered the questions comfortably because they were informed about the subject. In addition, questions asked from experts to the researcher, such as "is the usage of different materials at the same time possible?", "what are the maximum/minimum dimensions of production?" and "are there any samples in our country" were answered during the interview.

3.6. Delphi study first round answers and analysis

The taken notes and audio recordings were deciphered, and the keywords in the answer were noted at the end of each interview. Then, general answers were obtained for the question. After that, similar answers were grouped, and answer groups were listed.

As explained in the 2.1. section, if the answers to any question in the first round of the Delphi study reached a consensus between 51% and 100%, this question may not be presented to the experts again in the following rounds. For this reason, six design sub-processes and questions that reached the consensus value of 80% in the first round were not transferred to the second round.

3.7. Delphi study second round answers and analysis

Except for the six questions that reached a consensus in the 1st round, 15 questions given in Table 1 were represented to the experts in the second round. This presentation includes the answers given in the first round and the percentage value of experts. Here, since when the contrary opinions are eliminated, common ideas can be reached more easily without distorting the broad scale of opinions, the first five answers given by the highest number of experts were excluded were voted by the experts in the second round. Experts were asked to choose one of these answers given in the first round, so they learned the opinions of other experts and had the opportunity to evaluate their own answers once again. One expert from the first round did not want to participate in the second round. In the second round the experts responded on their own unlike the first round's face-to-face interviews.

3.8. Results and evaluation of Delphi study

The Delphi study was concluded in the 2nd round with the consideration that sufficient information was revealed and as there was no need for a consensus on a single absolute decision. The responses were analysed, and the number of experts, whether academicians or professionals and in what years of experience, were conveyed as shown in Table 1.

In Table 1, the first column (C1) contains the questions, and the second column (C2) contains the popular answers resulting from the Delphi study. In the third column (C3), the number of academician and professional expert groups are expressed in different lines, and the years of experience are expressed in different colours. Finally, the last column (C4) contains Delphi results transformed into redesign sub-processes to be applied to the selected detail design.

4. Redesigning the intersection area detail in line with Delphi study results and producing a 3D print prototype

In this section, redesigning was executed to test the usability of the theoretical Delphi results in the practical detail design process and for revealing the steps of the 3D printing detail design process if it is necessary. After that, a prototype was produced to test the constructability of the design and to test the general 3D printing rules on a sample production (Artuğ, 2020).

4.1. Redesign

The intersection area detail designed for today's technologies was redesigned to be produced with 3D printing technology by developing a design scenario with the research through design method, in line with the results obtained in the Delphi study. For this detail selection, firstly, the building elements related to the external envelope were classified according to the characteristics of "form, construction, structure and function" by using the literature. Then the detail combinations common to the "construction place" and "core structure" that can come together to form an intersection area detail were listed. Finally, from this list, the details given below were selected by considering features such as "diversity, frequency of use in the sector, adaptability to 3D printing technology".

- Exterior wall = Above grade (related to atmosphere) | construction on-site | non-load bearing | skeleton | ventilated
- Exterior wall opening = Window | with stud and header | multi layered

While developing the scenario, firstly, a "future environment" was generated. The future environment is based on the following assumptions:

- Year: 2030. This time was selected following the scenario described at the expert preliminary information stage on the Delphi study (using 3D printing in 2028, 2035 and 2050).
- Technology reality/development level: It was accepted that two industrial-scale printers exist today, which are "Fused deposit modelling" and "Freeze-form extrusion fabrication" working with the same practice (Material extrusion method) but producing separately, are combined.
- Climate: The same as the original climate of the selected detail, moderate, humid climate (Istanbul).
- Materials: Considering the detail designed for today's technology and its printability, molten aluminium, waste wood fibres, ceramic, and glass materials were selected to be used.
- Designer: An architect with sufficient knowledge about 3D printing technologies.
- Design output: 3D model

In those mentioned above, "future environment", the result obtained from each question in the Delphi study was transformed into the "redesign sub-process (Sub-P)", as shown in Table 1.

In line with the redesign sub-processes, the selected intersection area detail was redesigned step by step:

Step 0: Process design: In line with Sub-P7, the design and construction process specific to this example was designed firstly.

Step 1: Taking general decisions: According to Sub-P1A and "environmental design", 3D printer and material properties were determined. According to Sub-P3, standardization was observed when selecting element sizes and materials. According to Sub-P5, size, materials, and formal limitations were considered in line with "printer constructability". According to Sub-P11, ready-made details were not used; details specific to the selected intersection area were developed. Finally, according to Sub-P15, the print result was designed to be the final form, and post-production finishing was not applied.

Step 2: Making the main decisions of the wall elements with sketches according to Sub-P9A:

- Wall core: An aluminium frame wall core was designed by staying true to the sample detail. By reducing the joints in the Sub-P4 direction, the entire aluminium construction was designed as one piece. The skeleton form was formed so the insulation layer could be printed inside.

- Insulations: It was assumed that the thermal insulation in the direction of Sub-P6 and Sub-P14 was positioned between the aluminium construction and inside the aluminium frame, and polymer-bound waste wood fibres were used as material. The density of the thermal insulation was increased on the peripheries. Waterproofing was mainly dissolved in the outer covering and the ventilation gap.

- Cladding: In the direction of Sub-P8 and Sub-P12, it was decided to use a curvilinear surface that transfers its load to the extensions of the aluminium construction in the outer cladding, and a smooth, reflective surface formation directly adjacent to the wall core in the inner cladding. In addition, the coating was designed to be printed and installed in an atelier set up on the construction site, independent of the wall. Thus, it could be plugged in and out for changing or maintenance.

Step 3: Detailing the wall element and adding the window with the digital model: The window frame was designed in two parts. The first part was designed in such a way that the blind frame was removed in the direction of Sub-P16, and the sash would transfer the load directly to the aluminium construction, and they were produced together. On the other hand, the second part was arranged to be printed with the transparent element and polymer holders and be attached to the first part by fitting.

The sample detail model and the redesigned detail model for 3D printing are shown in Figure 3 comparatively.

Step 4: In line with Sub-P9B, taking a 1/2-scale mock-up print of the design: A mock-up was made with a 3D printer to test the design and see if it reached the desired level for printing.

Step 5: Revisions: Some mistakes in the model were corrected with revisions, such as increasing tolerance, separation of layer textures, etc.

Step 6: In line with Sub-P2 and Sub-P20, making the design ready for production: The digital model was transferred to the "Cura program", the material was introduced, layer densities and textures were defined, and the design order was determined by dividing it into parts.

Step 7: Production (printing process): The prepared models were printed piece by piece with a 3D printer and combined with the designed fittings.

4.2. Printing the detail prototype

In this section, the production of the prototype of the redesigned detail with a 3D printer is conveyed. Thus, both the constructability of the design and the general principles of technology are observed with the "prototyping" method. For this purpose, the digital model was made ready for printing by combining the components in the same layer, making size decisions, designing joints, converting to ".stl" format, checking the gap in the model, making layer settings, determining the need for support, the required amount of filament and the calculation of the time. Since this prototype is produced today, it is not a 3D printer designed in the "future environment" but an "Ultimaker3 Extended" desktop 3D printer.

The digital model, in which all the information was entered, was produced in 12 pieces in accordance with the printer size as follows:

- size (mm): 250 x 400 x 330 mm
- print time (h): 178 hour 40 minutes
- filament amount consumed (gr): 5.242 grams

After the prints were finished, the parts were taken from the printing table and cleaned the support elements with small hand tools (utility knife, side cutter, etc.). Photographs of the printed detail are given in Figure 4.

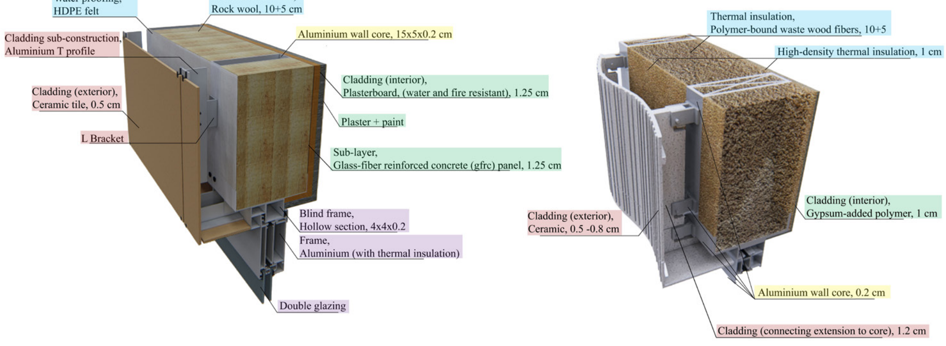

Figure 3. *Detail models designed for today's technologies and redesigned for 3D printing.*

5. Results and impacts

Architectural construction technologies continue to evolve, and this study aimed to determine the effect of the change in architectural construction technology on the design process in the context of "construction - design" interaction. Furthermore, the focus is on developing predictions about the impact of 3D printing technology, which has the potential to be used as an architectural construction technology in the future, on the detail design process. Thus, the results obtained from the studies can be grouped under two main headings (Artuğ, 2020):

5.1. Delphi study results

• When 3D printing technology is used as architectural construction technology, the main results obtained in the Delphi study regarding its effects on the design process are:

- The difference between on-site and off-site construction will decrease considerably in today's construction technologies in terms of ease of quality control.

- Joints and additional elements will almost disappear, and details will be "simplified" compared to today.

- The most significant factor that determines the design boundaries will be the properties of the 3D printer and the materials used.

- With 3D printing technology, searching for complex materials that meet multiple functions will increase and encourage material research in this field.

- "Design for climate and environmental data", "the process design requirement related to construction and design", and "model making as a design tool" will always exist regardless of the production technology used.

- It is expected that the role of the "architect" as a designer and controller will be preserved. However, there will be a "mastermind (artificial intelligence)" that dominates the entire design and production process.

• A balanced distribution was observed in the answers given by experts with different years of experience and professional practices in most of the questions on a subject related to architectural technology and design process. The only subject with a significant difference is the usage of sketch drawing as a design tool. Experts with 15 years and more of experience argue that sketching will continue to be used as it is today, while other experts think that sketch drawing will disappear over time.

5.2. Redesign and 3D printing results

• The results from the redesign process, which tested the usability of the theoretical Delphi results in the practical detail design process, are as follows:

- Unlike today's design process, it is essential to decide on every detail of the production technology at the very beginning of the design process. This need for knowledge may bring new and/or multiple specialities.

- With the principle of 3D printing, there is no need to use elements that meet only the joint function. However, it is seen that partial production may be preferred for reasons such as insertion and removal, expansion, and controllable size production.

- Compared to today's detail, the detail designed for 3D printing technology is "simplified" as the number of components decreases. This simplification will bring along positive developments such as efficient use of limited resources, shortening of construction time, less problem solving, and reduction of the problem of compatibility between components.

- It was observed that orthogonal or curvilinear form does not constitute a disadvantage during the production

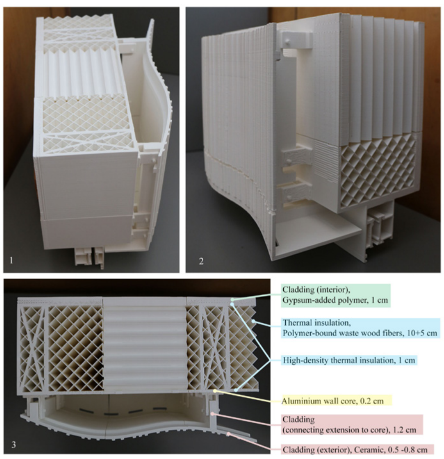

Figure 4. *Photographs of the prototype: 1 and 2 are from perspectives, 3 is a plan view.*

phase.

- The digital model, which is used as a tool in most design processes today, can be sent directly to the production process as an output, almost eliminating the process of defining the design. Minimizing identification will also reduce the margin of error while transferring the information.

• 1/1 scale prototype of an architectural building element was produced with a desktop 3D printer which belongs to today's technology and the process was reported. Thus;

- In 3D printing technology, although the machine error is almost zero, it is deemed necessary to have a controller at the time of production. However, considering that human intervention is required twice in 12 parts, this ratio is expected to decrease considerably with the development of technology.

- It was determined that it is necessary to leave a tolerance of 1-2 mm in the joints, depending on the material feature and the printed geometry. Determinig this tolerance amount by the manufacturers as a printer and material properties will guide the designer.

- Although using "support" elements that support the carriage of the printed element during printing does not create noticeable negativity in terms of time and cost during production, it does not comply with the principles of printing technology as it requires post-production processing. To not need this element, the technology should develop in vertical printing, multi-axis printing head, and high stability material.

6. Conclusion

In this study, the future use of 3D printing as a building technology is examined through the interaction of construction-design, and possible effective development aspects of the technology are predicted by the experts. The applicability of the results of the study is demonstrated by transforming these predictions into design inputs and applying them to a sample. As a conclusion:

• It was observed that both academicians and professional experts have a positive approach to the use of 3D printing technology as architectural construction technology.

• Data and facilitating information about the situations and criteria that may differ for the design processes they carry out while adapting to developing technologies are presented for architectural offices.

• By presenting the advantages of 3D printing technology and the ongoing studies, the construction sector is encouraged to focus on this issue.

• An example of the Delphi forecast method, chosen to make a future assessment in the field of architectural construction technology, is presented.

• Throughout the redesign for the 3D printing technology experience, it was not encountered any opposite thought to the Delphi results, and redesign sub-processes could be applied easily.

• It was observed that using a 3D printer does not require long-term specialist training. When an appropriate interface is designed, including the design process, it is thought that the user can also be involved in the production process. In some exceptional cases, the roles of "designer-producer-user" can be combined by eliminating intermediaries.

It has great importance that the research groups and industry stakeholders in Turkey should be included as a team to studies conducted at the international level over the past decade. In this study, various data have been created for future architectural technology education and research on the use of 3D printing in architecture. However, due to the lack of a large-scale printer that can be accessible, the prototype production with a desktop printer and a single material may have prevented some results from being observed. The production of large surfaces, the use and harmony of different materials, and the adaptation of existing workforce and tools are some of the issues that need to be examined. Based on these data, in prospective studies;

• Detail design samples produced by 3D printing can be increased,

• Performance (thermal, water, sound, etc.) characteristics of 3D printing technology can be determined.

• Today's construction technologies and 3D printing technology as architectural construction technology can be compared by strengthening the data obtained from experimental studies.

Acknowledgement
This study was supported by the ITU Scientific Research Projects Coordination Unit (ITU - BAP).

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