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INTEGRATION OF DIGITAL FABRICATION LABORATORIES AND COMPUTATIONAL DESIGN INTO THE ARCHITECTURE CURRICULUM IN TÜRKİYE

TÜRKİYE'DE DİJİTAL ÜRETİM LABORATUVARLARININ VE HESAPLAMALI TASARIMIN MİMARLIK ÖĞRETİM PLANI İLE ENTEGRASYONU

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Abstract

This paper aims to examine the current state of digital fabrication and computational design integration with architectural design education at the undergraduate level in Türkiye and proposes recommendations for future development. This study examined nine universities with digital fabrication laboratories under three headings: digital design, digital fabrication, and spatial reflections. Content analysis of courses and spatial analysis of fabrication laboratories have been implemented as a methodology. Furthermore, this research employed semi-structured interviews with the relevant faculty members to gain a comprehensive understanding of the role of digital design and fabrication in architectural education and spatial conditions. According to the results, architectural departments are expanding by constructing new laboratories, incorporating sophisticated equipment, and reorientating the curriculum to align with technological advancements and shifts in architectural paradigms. However, this research also indicates the limitations, such as implementation costs, safety problems and resistance to a new curriculum for implementing digital fabrication technologies. The findings of this research indicate the potential benefits of integrating advanced fabrication tools into current curriculum, with the necessity of making elective courses mandatory while integrating them into the undergraduate curriculum.

Keywords: Architectural Design, Digital Design, Digital Fabrication, Design Pedagogy.

Öz

Çalışmanın amacı; Türkiye'de lisans düzeyinde sayısal üretim ve hesaplamalı tasarımın mimari tasarım eğitimiyle bütünleşme düzeyini, bu bağlamda üniversitelerin mevcut durumunu incelemeyi ve bu çıkarımlar doğrultusunda öneriler sunmayı amaçlamaktadır. Bu çalışmada sayısal tasarım, sayısal üretim ve mekansal yansımalar olmak üzere üç başlık altında dijital üretim laboratuvarları olan dokuz üniversite incelenmiştir. Metodolojik olarak; derslerin içerik odaklı analizi ve sayısal üretim laboratuvarlarının mekansal analizi yapılmıştır. Ayrıca, bu araştırmada sayısal tasarım ve üretimin mimarlık eğitimi ve mekansal koşullardaki rolü hakkında kapsamlı bir anlayış kazanmak için öğretim üyeleriyle yarı yapılandırılmış görüşmeler kullanılmıştır. Sonuçlara göre, mimarlık bölümleri yeni laboratuvarlar inşa ederek, gelişmiş araçları bünyesine katarak ve müfredatları teknolojik gelişmeler ve mimari paradigma değişimine paralel olarak genişlemektedir. Ancak bu araştırma uygulama maliyetleri, güvenlik sorunları ve dijital üretim teknolojilerinin uygulanması için yeni bir müfredata karşı direnç oluşması gibi sınırlamaları da ortaya koymaktadır. Araştırmanın bulguları, gelişmiş sayısal üretim araçlarının mevcut mimarlık lisans müfredatına entegre edilmesinin ve ilgili seçmeli derslerin zorunlu hale getirilmesinin gerekliliğini göstermektedir.

Anahtar Kelimeler: Mimari Tasarım, Dijital Tasarım, Dijital Üretim, Tasarım Pedagojisi.

INTRODUCTION

Cognitive processes, pedagogical approaches, and architectural practice have been influenced by industrial developments and the increasing usage of digital technologies in architecture. The changes as a result of the advent of industrial development have become vital issues in architectural education. From a pedagogical perspective, these changes in architecture create an opportunity for architectural students to explore materials and experience hands-on learning environments. Many universities have integrated digital design courses and digital fabrication practices into their curricula over the past decade. Such courses equip students with the skills to use these innovative tools effectively.

Furthermore, digital technologies have also had impact on the spatial organisation of universities. As Celani (2012) states, in many universities, the ateliers within the faculties of architecture were initially transformed into rapid prototyping spaces. Following this, these spaces are undergoing a process of transformation into digital fabrication laboratories. The objective of this study is to examine the ways in which course curricula in architecture departments are evolving and how this transformation is reflected in the spatial organisation and equipment used in fabrication laboratories.

In this study, the undergraduate course contents of the architecture departments of nine foundation and state universities in Türkiye are examined to understand the reflections of transformation in their pedagogical approaches. These courses were analysed to understand the reflections of transformation in their pedagogical approaches. This study also applied interviews with faculty members from three prominent universities with digital fabrication laboratories within the scope of this research. Lastly, this research examined the fabrication laboratories (FabLabs) of the selected universities to reveal the spatial requirements of the courses. This study compared the university's layout of FabLabs course contents and lecturers' approaches to digital design and fabrication. It revealed different approaches and educational strategies among universities.

In consequence of the advancement of technology and the transformation of architectural practice by digital design and fabrication tools, it is imperative that architectural education be updated accordingly. In this context, the research is important in terms of contributing to the literature as guiding research for architecture departments to update their curriculum through the findings obtained in terms of approach and content and filling the gap in understanding how faculty members pioneer new technologies and applications and the spatial requirements of this transformation.

PARADIGMA SHIFT IN ARCHITECTURE PRACTICE AND EDUCATION

'Paradigm shift' is a concept first introduced by Kuhn in his book 'The Structure of Scientific Revolutions'. Kuhn (1996) defines 'paradigm' as a model or pattern of specific values, beliefs, and habits that are based on scientific research and 'change' as the emergence of scientific theories and practices. The concept of a paradigm shift includes changes in both theory and practice. According to Kuhn, paradigm shifts arise from destructive changes that occur when the number of problems in a discipline increases, and pioneers in the field focus on these problems (Hairston, 1982). The concept of paradigm shift is discussed in various fields, including sociology, education, economics and also manufacturing systems.

During the first half of the 20th century, the industrial world was dominated by Fordism. Fordism is derived from the capitalist labour process introduced by Henry Ford in the 1920s, which involves the technical and social division of labour in production of standardised goods and is based on a growth cycle of mass consumption and mass production (Jessop, 1992). Although it has potential for efficiency and low cost, the Fordist production process has been criticised for its tendency to standardise users regarding psychology and skills (Gramsci, 1999). Furthermore, it has been claimed that this standardisation, following Fordism's principles, was developed to maintain control over society (Antonio & Bonanno, 2000; Gramsci, 1999). The post-Fordism paradigm emerged as a solution to the contradictions and crisis tendencies of the Fordist system. Unlike Fordism, post-Fordism involves a production process that employs flexible machines, systems, and labour (Jessop, 1992).

Changes in the mode of production have impacted the evolution of the architecture. The field has undergone a transition from Fordism, which relied on mass production and standardisation, to post-Fordism, which involves a more flexible and customisable production process. The industrial paradigm of Fordism involves mass production and product standardisation to reduce costs and increase affordability (Dunham-Jones, 1997). This paradigm shows similarities with the modernist paradigm for architecture. However, the modernist paradigm's emphasis on standardisation does not consider users as unique individuals with distinct physical and psychological characteristics. Instead, it views users generally as healthy individuals with average body measurements. In contrast, the post-modernist paradigm emphasises the unique characteristics of individuals. The concept of mass customisation has been the subject of increasing discussion in the literature since the late 1980s (Da Silveira et al., 2001; Fogliatto et al., 2012; Piller, 2004; Tseng et al., 1996), and is a defining feature of the new industrial revolution (Yao & Lin, 2016).

These paradigms have greatly influenced architecture education in their respective eras. For instance, the Modernist paradigm was closely linked to the approach of the Bauhaus, which was the most influential art school of the 20th century. The Bauhaus approach is regarded as a key element of the modernity movement. Efforts were made under 'modernism' to re-establish unity between artistic and technical production, which had been separated by industrial production (Siebenbrodt & Schöbe, 2009). The book "Architect's Data" by Ernst Neufert (1980), one of the first students of this school, shows traces of standardisation, one of the essential features of the modernist paradigm. In his renowned book, Neufert, who Walter Gropius trained, included standardized spatial dimensions and detailed descriptions of elements at various scales (Meister, 2020).

The Bauhaus school originated from the Bauhaus Ecole, which shares its name. It is a school of design, architecture, and applied arts founded by Gropius in 1919. Despite its relatively brief existence of only 14 years, this school remains influential in architectural education today. The pedagogical approach of the Bauhaus was shaped by the modernist paradigm, and its mission was to use the possibilities of new production techniques with the slogan "new unity". Bauhaus was influenced by the art and craft movement of its time (Findeli, 2001), and the idea that these disciplines should interact with architecture shaped this school. Therefore, the integration of architecture and craft was emphasized, and the course contents were designed accordingly. The aim of the Basic Design education given in this school includes the study of not only composition but also materials and tools (Bell et al., 2010).

However, the Bauhaus motto, known as 'Art and Technology-A New Union' (Siebenbrodt & Schöbe, 2009), involves the integration of science, as found by Findeli (2001). Findeli claims that the ideal model of Bauhaus characterised by the "three-tiered unity of technology/art/science" (Amundsen, 2018). The Basic Design courses at Bauhaus established a connection between craft and technology by prioritising aesthetic principles. Artistic elements, such as colour, shape, texture and visual quality, were addressed, and in this way, young designers were encouraged to find their unique style. In this sense, Itten (Bell et al., 2010), who gave preliminary courses at the Bauhaus, emphasizes the importance of self-discovery of the form and its unique identity. On the other hand, Keller (Bhatia & Sharma, 2014) describes the characteristic of modernism with the pressure called "scientism" and identifies it as "forced to question its methods, its principles, its subject matter, and its legitimacy". Moreover, Findeli (2001) cites this repression as the reason for the failure of the Bauhaus' ideal model in the New Bauhaus and states that it failed not only in the New Bauhaus (1937-1955) but also in other archetypes, such as the Bauhaus (1919-1928) and the Hochschule Für Gestaltung (1958-1968), emphasizing that each time one of the triads that should have intersected was excluded (Figure 1).

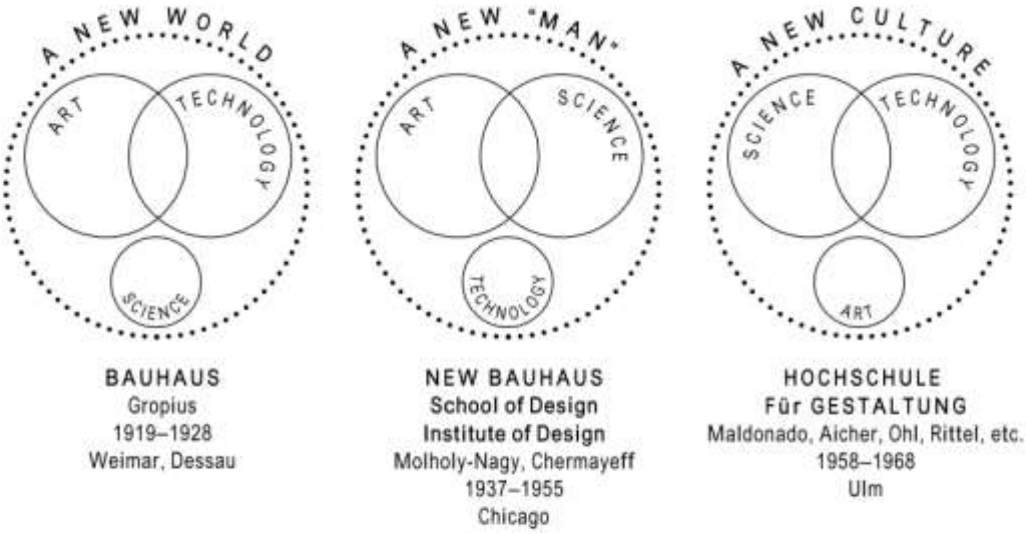

Figure 1. Schematic drawing of the Bauhaus archetypes (Findeli, 2001).

Siebenbrodt and Schöbe (2009) emphasise the scientific approach and standardisation principles of the Bauhaus, which originated at 1928. Standardisation can be described as a result of industrial developments and as Bauhaus's aim. Although the integration of art, science, and technology is desired, it is evident that art is practically excluded from this formation. Although the Bauhaus proposal clearly emphasized the balance between the three components of architecture, it could not be realised because of the pressure of scientism. Today, Bauhaus remains influential in architectural pedagogy, but its dominant character in architecture, rooted in the modern era and standardisation, is criticised by various theorists (Antonio & Bonanno, 2000; Beorkrem, 2017; Paio et al., 2012a).

Architecture is currently undergoing a transformation driven by the development of technologies. This transformation is influenced by scientific developments such as artificial intelligence, digital design environments, and parametric and algorithmic ways of thinking. These tools and methods enable the exploration of previously unimaginable possibilities. As Terzidis (Bodea et al., 2020) states, these technologies allow us to exceed the limits of the human mind with algorithms. In the early design phase, machine learning and architectural expertise are already used as design assistants (PlanFinder, 2024). Therefore, the question of how these developments will transform architectural practice and how architectural education will adapt accordingly has been discussed in the literature (Çil et al., 2007; Çinici, 2012; Gündüz et al., 2018; Gürsoy, 1920; Özkar, 2004, 2007; Sehgal, 2015; Uygun, 2013; Yazici, 2020).

The development of computer technologies and the challenges faced in the manufacturing process using traditional production methods have led to a search for new design and manufacturing methods (İşbitiren, 2020).This evaluation in information and communication technologies has influenced architecture and architectural education. Architecture has evolved into a discipline that focuses on the production and design process by enabling the processing of information and fostering creativity and decision-making process (Çağdaş et al., 2015).

The acceptance of computational design by designers and architects, along with the ability to analyse designs in terms of various performance criteria, originated with the introduction of these tools in the 1980s (Caetano et al., 2020). Caetano and Leitão (2020) suggest that computer-aided design, building information modelling, and various analysis and simulation tools have influenced the development of computational design tools. The emergence of computer-aided design tools in the 1980s, initially in two-dimensional and later in three-dimensional drawings, followed by the introduction of building information modelling systems such as ArchiCAD to the construction sector, marked significant initial steps in the proliferation of computational design approaches. Subsequently, in the 1990s, the development of software such as Rhinoceros, followed by SketchUp and Grasshopper in the 2000s, played a crucial role in the advancement and widespread adoption of computational design approaches. Computational design uses these computational capabilities (Caetano & Leitão, 2020). However, beyond that, it is a design process that involves the algorithmic thinking that architects employ in their design processes (Çolakoğlu & Yazar, 2007). It addresses design's conceptual, experiential, and visual aspects through intuitive and analytical methods (Çağdaş et al., 2015).

TRANSFORMATION IN ARCHITECTURAL EDUCATION BASED ON TECHNOLOGICAL DEVELOPMENTS THROUGH DIGITAL DESIGN AND FABRICATION TOOLS

Digital design environments allow the realisation of designs that go beyond even the boundaries of free forms and human imagination (Terzidis, 2003) and the advent of digital fabrication technologies has enabled the realisation of such designs within the architectural discipline. The effects of these technologies, which can be grouped into additive, subtractive, and transformative manufacturing techniques (Paio et al., 2012b), on architecture are being discussed today. However, the use of tools such as CNC, whose history dates back to the 1950s (Zhang et al., 2011), actually has a much longer history. Today, 3D printers have become a commonplace item in almost every home and laser cutting tools in almost every architecture faculty. Furthermore, robotic tools are gradually spreading in architecture faculties, and these developments imply a significant transformation in architectural practice.

These tools not only enhance the relationship between fabrication and design, making architects more effective, but also, according to Celani (Celani, 2012), place architectural faculties in a more industry-oriented context. Various research projects are being conducted by institutions such as Massachusetts Institute of Technology, Stuttgart University, and Delft University, as well as by educators and practitioners such as Achim Menges, Gramazio Kohler, and Neri Oxman (Bodea et al., 2020; Menges & Reichert, 2015; Oxman et al., 2014). Architects are developing innovative technologies and approaches that shape the industry and, in some cases, designing their tools. This transformation shifts the role of architects beyond that of mere of being collaborators with the industry and positioning them into a more transformative position (Sharif & Russell Gentry, 2015). Recent studies have identified a potential framework for shifting away from the traditional view of the designer as an idealistic intellectual operating separately from the construction process. Instead, there is a growing emphasis on a methodology that integrates digital information, physical materials, and the entire construction lifecycle (Jenny et al., 2022).

Here, the question of how design education will evolve with respect to these technologies is essential, and the answer is discussed in the literature (Carpenter, 2014; Celani, 2012; El-zanfaly, 2015). The advent of digital technologies had an impact on architectural education (Mao-Lin, 2006; Yıldırım et al., 2010). This has resulted in the necessity to assess the impact of contemporary digital design and production technologies on design processes in architectural education (Gül et al., 2013). In this context, it is observed that the graduate approaches of these pioneering universities have transformed toward interdisciplinary collaborations, where different disciplines engage in joint projects within these laboratories. On the other hand, a transformation is also evident in undergraduate education. Desktop robots, in particular, have become a part of production workshops and are integrated into undergraduate education. These tools are generally accessible to students who meet specific criteria or who have the assistance of technicians in the school. For instance, at Lawrence Technological University (LTU), these tools are available to students who have taken courses in digital fabrication or robotics (LTU, 2024). Lecturers contribute to the design education literature by experimental studies such as integrating robotic fabrication with basic design courses (Yazar et al., 2023a). There are also studies that present curriculum to introduce CAD and CAM tools into architecture design education (Ünlü & Alaçam, 2020).

The utilisation of these technologies offers designers greater flexibility in the design process, while simultaneously facilitating the monitoring of the design process in a conscious manner (Yıldırım et al., 2010). A research conducted at 18 universities in Turkey revealed that courses related to digital technologies are predominantly included in the category of communication-presentation and are widely employed in design and project-based curricula. However, these courses constitute approximately 10% of the overall academic curriculum (Gül et al., 2013). In order to integrate digital fabrication methods into architectural education, educators have developed a variety of strategies. One such strategy is the constructivist learning process, which assigns an active role to the student and includes a series of exercises with fabrication tools and processes (Oktan & Vural, 2022).

In conclusion, the utilisation of computational design instruments by designers and architects has occurred concurrently with the advent of two-dimensional and three-dimensional computer-aided design instruments since the 1980s. Subsequently, the advent of software such as ArchiCAD, Rhinoceros, SketchUp, and Grasshopper in the 1990s facilitated the adoption and propagation of computational design methodologies (Caetano et al., 2020). Since the 2000s, these programs have been incorporated into the curriculum of educational institutions. In particular, they have become a standard feature of architectural education over the past 20–25 years (Mıhlayanlar & Tachir, 2019). Following the incorporation of these software applications into the architectural curriculum, discussions pertaining to digital design and fabrication commenced with frequency. To integrate digital thinking into the architectural curriculum, a variety of design tools were employed in workshops, weekly exercise, lectures and experimental studies (Allam & AlaÃ§am, 2021; Oktan & Vural, 2022; Yazar et al., 2023a). In summary, technological developments have prioritised practice-based competencies in architectural education curricula and led to more engagement in practical activity in architecture and inevitably increased practice integration into architectural education.

METHODOLOGY

The objective of this paper is to examine the potential integration of digital fabrication and computational design within the context of architectural education at the undergraduate level. This investigation is guided by a research framework that encompasses three core concepts: digital design, digital fabrication, and spatial organisation (fablabs). Using this framework, this study analysed the institutions in Türkiye with Digital Fabrication Laboratories based on information from the official websites of state and foundation universities. The universities included in the analysis are Istinye University (ISU), Istanbul Technical University (ITU), Istanbul Bilgi University (IBUN), Karadeniz Technical University (KTU), Yaşar University (YU), Gebze Technical University (GTU), Eskişehir Technical University (ESTU), Middle East Technical University (METU), and Izmir University of Economics (IEU). The official websites of these universities were analysed to determine the current course contents and laboratory facilities related to digital design and fabrication. Following this preliminary examination, the research proceeded to concentrate on the architectural departments that possess their own fabrication laboratories with robotic arms. Therefore, faculty members were interviewed for a deeper analysis (Table 1). The interviews provided additional and updated information to supplement the limited data obtained from the universities' websites, which were selected as case studies. Course contents were analysed separately for each institution under the headings of digital fabrication, including courses, digital design courses and digital fabrication laboratories (Figure 2), and the findings were presented.

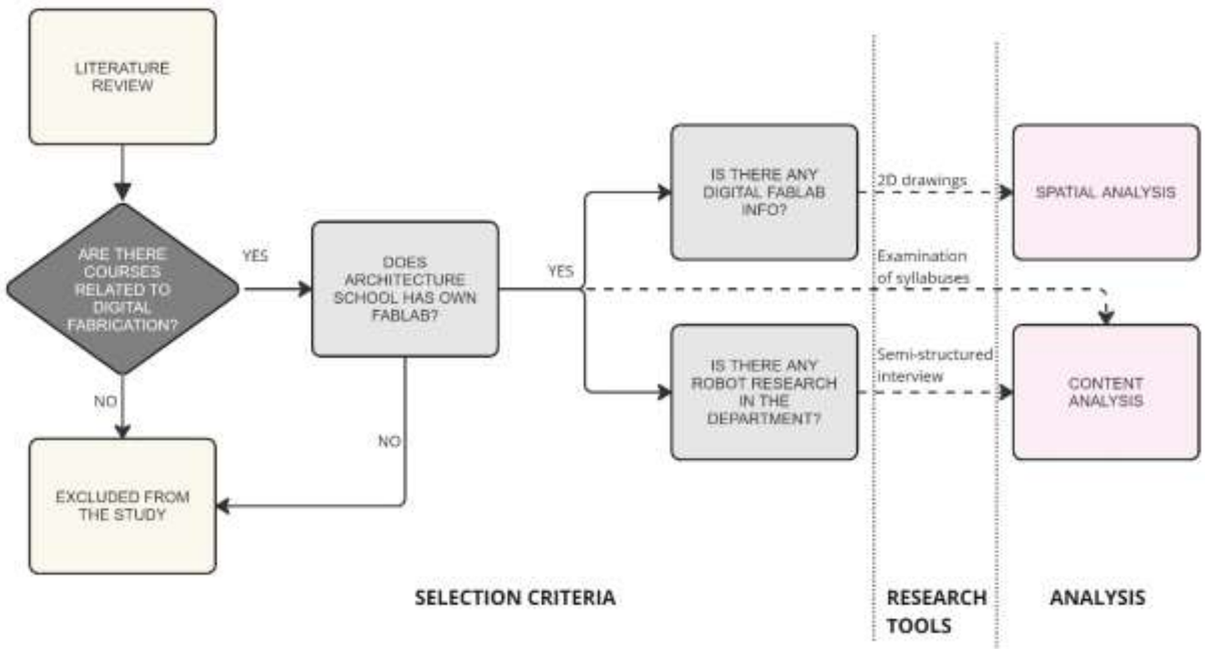

Figure 2. Research Methodology.

Lastly, the components of the Fablabs of the four universities have been mapped through observations of authors and information obtained from the official website. The spaces in which the FabLabs are composed, how they are organiSed, and the relationship between the spaces have been analysed.

Table 1. Research design of the methodology.

Universities	**Interview with faculty members**	**Analysing of course content**	**Analysing of fablabs' spatial layout**
ISU	-	Source: (ISU, n.d.-b)	Source: (ISU, n.d.-a)
ITU	Assoc. Prof. Dr. Sema Alaçam	Source: (ITU, n.d.-a)	Source: authors' observations
IBUN	Prof. Dr. Tuğrul Yazar	Source: (IBUN, n.d.-a)	NA
KTU	Prof. Dr. Serbülent Vural, R.A. Barıs Çaglar, R.A. Dr. Selin Oktan	Source: (KTU, n.d.-a)	Source: authors' observations
YU	-	Source: (YU, n.d.-a)	NA
GTU	-	Source: (GTU, n.d.)	NA
ESTU	-	Source: (ESTU, n.d.-a)	NA
METU	-	Source: (METU, n.d.-a)	Source: (Arkitera, n.d.-a)
IEU	-	Source: (IEU, n.d.-b)	NA

The interview questions were devised in accordance with the three research themes of digital design, digital fabrication and spatial conditions related to fablabs (Table2). Additionally, general questions were posed regarding the role of these courses in the relationship between the architectural education and practice, as well as outcomes.

Table 2. Research protocol.

Theme	Main questions and sub-questions	Purpose
Digital Design	• Can you describe the manner in which you address the theme of digital design in the '..............' course you teach? • In what manner does this course contribute to the broader context of architectural education?	To identify and analyse the ways in which digital design are addressed in architectural education.
Digital fabrication	• Can you describe the manner in which you address the theme of digital fabrication in the '..............' course you teach? • Can you explain the rationale behind the decision to include this course in the curriculum of architectural education? • Can you describe any practices you undertake as part of this course? What difficulties have you encountered in these practices? • On what scale are the practices being carried out? • What materials are employed in Fablabs? What influenced the selection of these materials? Are there any environmentally friendly materials among them?	To gain a comprehensive understanding of the role of digital fabrication in architectural education and put forward the content of these courses, along with the practices and theory employed
Spatial Organisation (Fab-labs)	• What was the rationale behind the decision to establish Fablab in the Department of Architecture? What kind of tools do you have? • How many hours of your course are conducted within the classroom setting, as compared to those held within the laboratory facilities of FabLab? • Do you utilize the full range of tools available in the FabLab within the context of the course curriculum?	To identify the spatial requirements associated with digital fabrication-related courses.
Role of courses between architectural design and practice	• What is the role of digital fabrication laboratories in the relationship between architectural education and practice in this regard? • What are the learning outcomes of digital fabrication courses in relation to the professions of architecture and other related fields? • What is the impact of digital fabrication on architectural practice? What should be the impact of digital fabrication on architectural practice?	To examine the contribution of related courses to the preparation of architecture students for the architectural profession.

FINDINGS

Reflection of Digital Design Courses on Undergraduate Architecture Education in Türkiye

ITU (n.d.) offers three computer-aided design courses that support digital fabrication applications. The "Information Technologies in Architecture" course teaches computer-aided architectural design models and approaches, generative systems, and innovative design approaches and applications. On the other hand, the course 'Introduction to Computational Design Tools and Methods in Architecture' utilises Rhino and Grasshopper applications. It introduces various digital design and architectural fabrication technologies (ITU, n.d.-a). The use of additive and subtractive fabrication methods, robotic fabrication methods, and approaches to form finding using both analogue and computational methods were introduced in the course titled "Design and Fabrication Techniques in Architecture".

ISU (ISU, n.d.-b) provides “Digital Design 1” as a compulsory course in the second semester and “Generative Systems in Architectural Design” as an elective course in the third semester. The compulsory course employs the Rhino digital design tool, while the elective course teaches the impact of generative formalisation approaches on the design process. The IBUN curriculum (n.d.-b), on the other hand, includes courses on computational design, such as the first-semester course titled “Architectural Geometry”, the 2nd-semester course titled “Design Computing”, and the elective course titled “Computational Building Information Modelling”. Furthermore, the “Basic Design” course is designed using a computational approach, as noted by Yazar (2023).

YU (n.d.-c) offers courses in computational design, including the compulsory course “Introduction to Computational Design” and the elective courses “Complex Manufacturing Models in Architecture”, “BIM-Building Information Modelling”, and “Architectural Modelling and Visualisation”. On the other hand, according to the course curriculum of GTU (GTU, n.d.) the courses that can be evaluated in this context are the compulsory course “Computer Applications in Architecture” and the elective courses “Three-Dimensional Modelling Techniques” and “Computational Design in Architecture”.

According to the curriculum of ESTU (n.d.-b), the compulsory course “Computer Applications in Architecture” and the elective courses “Computer Aided Design I, III, V” are digital design courses. On the other hand, “Computer Aided Architectural Graphics” and “Computer Aided Drawing” are compulsory courses, and the elective courses titled “Digital Based Design”, “Architectural Geometry”, and “Introduction to Computational Design” at IEU n.d.-a) can be considered in this context. Furthermore, two compulsory courses in the METU Architecture curriculum (METU, n.d.-b) cover digital design topics such as parametric design, generative systems, and BIM, in addition to digital fabrication.

Reflection of Digital Fabrication Courses on Architectural Undergraduate Education in Türkiye

According to the syllabus published on the ITU’s official website (ITU, n.d.-b), computational design is taught in the second semester as a compulsory course called "Introduction to Computational Design Tools and Methods in Architecture". Laser cutting tools, including digital fabrication applications, are also used in this course. On the other hand, an elective course called "Design and Fabrication Techniques in Architecture", in the curriculum includes digital fabrication applications and introduces students to digital fabrication tools. At ITU, the use of tools or materials and the context of the space are considered part of the course. In a sample application to support the learning-by-doing experience, students were asked to digitally model a void in the school and then design it (Alaçam, 2022). In addition to these exercises, Alaçam (2022) stated that students were encouraged to design their own CNC and draw robots with an exploratory project.

According to the IBUN course curriculum (IBUN, n.d.-a) students are introduced to computational design logic within the compulsory Basic Design 1 and 2 courses in the first and second semesters. They are also introduced to digital fabrication techniques in Basic Design 2. In addition to these courses, three robotic fabrication courses have been designed for students to take as electives in the following semesters (Robotic Fabrication in Ecological Structures, Digital Making and Control in Robotic Fabrication, Design for Advanced Robotic Fabrication) (IBUN, n.d.-a). According to Yazar

(2023) the first elective course explores potential designs under ecological structures, while the second introduces students to robotic fabrication. The last of these courses has content to encourage students to create creative designs with these tools.

In an experimental study on integrating robotic production into the basic design course of IBUN ((Yazar et al., 2023b) was conducted in three stages: understanding the material and technique, first encounter with the robotic arm, and robot-mediated design changes. According to Yazar et al. (2023) in this study, students successfully shifted parameters and functions from the manual environment to the robotic environment.

According to the KTU course curriculum, (KTU, n.d.-a) the 5th-semester elective course “Digital Fabrication in Architecture” includes digital fabrication applications. According to Vural (Vural et al., 2023), in addition to this course, content, including digital fabrication applications, was designed by a pilot group selected in the first-semester Basic Design I compulsory course in the fall semester of 2022-2023. In addition, while Vural et al., (2023) states that the content of the Computer Aided Modeling I, II, and III elective courses may change from semester to semester, he emphasises that in the 2021–2022 academic year, fabrication techniques were studied in the Computer Aided Modeling III course instead of these courses.

According to the curriculum of ISU (ISU, n.d.-b), two courses (Digital Design Studio and Parametric Design) can be taken as electives in the second and third semesters of the department. The course content was designed according to computer-aided design processes. In addition to computer-aided design, these courses include digital fabrication applications. According to the curriculum of YU (YU, n.d.-b), digital fabrication techniques are introduced to students in the elective course “Digital Crafts in Architecture”. According to the current course syllabus and contents on the official website of METU (METU, n.d.), two required courses (Digital Media in Architecture I and II) in the university’s third and fourth semesters include digital fabrication practices. On the other hand, in the other universities examined (ESTU, GTU and IEU), no course included digital fabrication applications in the curriculum according to the course programs and contents (ESTU, n.d.-b; GTU, n.d.-a; IEU, n.d.-a).

Reflection of Digital Design and Fabrication Courses in Undergraduate Education on Space

ITU [64] has two digital fabrication laboratories: the Digital Fabrication Laboratory and the Innovation and Modelling Laboratory (IMLAB). IMLAB covers an area of 150 m2 and includes production, storage and working areas (Figure 2). It has 1 CNC machine, 3D printers, a knitting machine, a ceramic lathe, a projection device, and electronic materials. The Digital Fabrication Laboratory is equipped with a three-dimensional printer, a laser cutter, and a CNC machine. The University also has a six-axis robot, which is currently inactive. According to Alaçam (2022), the school’s equipment and digital fabrication laboratories are not used efficiently. Conversely, 3D printers and laser cutting tools are actively used in related courses [61]. According to Alaçam (2022), a robot arm with features such as image recognition, moving objects, and placing colourful mosaics was recently purchased for a research project.

The ISU Digital Fabrication Laboratory spans an area of 150 m2 and comprises a warehouse, classrooms, and workshops (Figure 2) (ISU, n.d.-a). Digital milling machines, laser cutting machines, six 3D printers, and a 3D scanner are located in separate workshop areas in this laboratory. On the other hand, the IBUN Digital Fabrication Laboratory (IBUN, n.d.-b) has a CNC machine, a laser cutting machine, a six-axis robot, and six 3D printers. Yazar (2023) notes that undergraduate students use laser cutters and 3D printers as the most frequently used machines in the laboratory. Furthermore, according to their website, the laboratory at Yaşar University has seven 3D printers and one vacuum injection moulding machine.

KTU’s laboratories (KTU, n.d.-b) comprise two workshop areas (Figure 3). The laboratory has a plotter, 3D printer, a six-axis robot, and a laser cutting machine. Vural et al. (2023) also notes that different end effectors can be attached to the robot arm to perform handling, hot cutting, and milling operations. Three-dimensional printers and laser cutting machines are the most frequently used among these tools. Vural et al. (2023) states that although experiments have been conducted on using robotic tools with undergraduate students, a heavily loaded curriculum must be taught.

The digital fabrication laboratory at ESTU comprises two distinct areas: a 3D printer, robotic tools, and a laser cutting machine, in addition to a workshop area. Additionally, the Digital Fabrication Laboratory at IEU (n.d.-a)spans 711 m2. It has four 3D printers, two laser cutting machines, three VR machines, and various cutting, drilling, and engraving machines.

The Fabrication Laboratory at METU (Arkitera, n.d.-b) was completed in 2017 and spans 1100 m2 (Figure 2). The laboratory is divided into three areas: one for materials such as metal, timber, or ceramics that may cause dust formation and one for CNC device usage. Another laboratory is for activities such as prototype production, three-dimensional output, earthquake simulation, photo shooting, gathering, and meetings, which are defined as interaction workshops. The third laboratory is for general fabrication and offices (LTU, 2024). According to the official university website, the department has two robot arms.

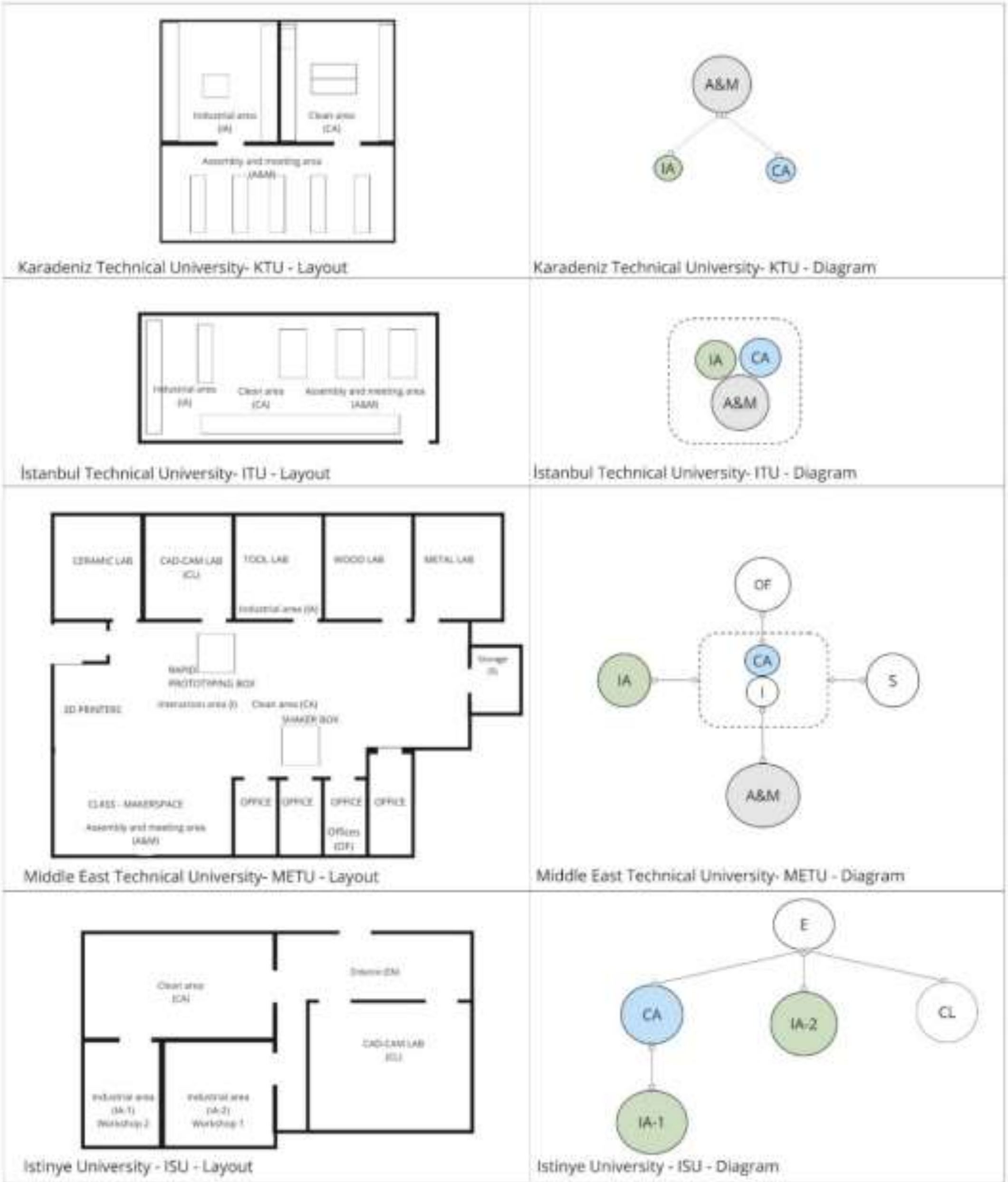

Figure 3. Schematic drawing of universities' layout typologies.

CONCLUSION

Compulsory digital fabrication courses are typically offered in the first three semesters at selected universities, with elective courses available in subsequent semesters. At Istinye University, digital fabrication is only included in elective courses. In contrast, it is excluded from the curriculum at ESTU, GTU, and IEU. State Universities, ITU and KTU; Foundation Universities, ISU, YU, and IBUN, offer courses on digital fabrication techniques, including compulsory and elective courses. Only IBUN offers courses on robotic fabrication (Table 3). Although METU has two robotic arms, there is no information on robotic fabrication in the architecture undergraduate course.

Table 3. Courses that include digital fabrication.

University	Elective		Compulsory	
	Semester	**Course count**	**Semester**	**Course count**
ISU	2	3	3	2
ITU	7	1	2	1
IBUN	3,4,5,6,7,8	3	2	1
KTU	5	2	1	1
YU	NA	2	-	-
GTU	-	-	-	-
ESTU	-	-	-	-
METU	6,7,8	2	4	2
IEU	-	-	-	-
Total		13		7

Upon analysis of digital design courses, it is evident that compulsory courses are typically completed within the first two semesters, with digital design topics being included in elective courses in subsequent semesters. Besides courses in the METU curriculum, most of these courses appear to be tool-oriented, focusing on teaching computer-aided design environments. However, computational design topics are prevalent in the curriculum, particularly at METU (Table 4). In contrast, YU, ITU, and IBUN offer only a limited number of compulsory courses in this area.

Table 4. 3D Modelling and Computational Design topics according to the course contents.

University	3B Modelling				Computational Design			
	Elective		Compulsory		Elective		Compulsory	
	Course count	Semester	Course count	Semester	Course count	Semester	Course count	Semester
ISU	-	-	1	2	1	3	-	-
ITU	1	4	-	-	2	4	1	2
IBUN	-	-	-	-	1	7-8	2	1
KTU	2	3,4	1	2	2	3	-	-
YU	2	NA	-	-	1	NA	1	3
GTU	1	2	1	2	1	3-8	-	-
ESTU	3	3,5,7	1	2	-	-	-	-
METU	1	6,7,8	-	-	5	6,7,8	2	3,4
IEU	1	NA	2	2,3	2	NA	-	-
Total	11		6		15		6	

Based on the course programs and contents on the official websites of these institutions, the tools listed in the Digital Fabrication Laboratories of these universities were also examined within the scope of this study. Accordingly, only ITU, KTU, METU, and IBUN have six-axis robots. Almost all institutions have 3D printers and CNC/Laser cutting tools. Due to the widespread use and accessibility of these tools, many 3D printer tools are found in these laboratories (Table 5). Although CNC cutting tools exist in almost all these institutions, laser cutting tools and 3D printers are mainly used.

Table 5. Digital fabrication laboratory tools and equipment.

University	Robot (6 axis)	3B-Printer	CNC/Laser Cut	Various Electronic Equipment and Machines
ISU	-	6	1	1
ITU	1	2	3	1
IBUN	1	6	2	-
KTU	1	1	1	NA
YU	-	7	NA	1
GTU	-	NA	1	NA
ESTU	-	NA	NA	-
METU	2	NA	4	7
IEU	-	4	2	1
Total		12		7

Finally, the spaces identified in the FabLabs examined as case studies in the research were classified as follows: industrial area including workshops, clean area consisting of 3d printers, learning space, computer lab, offices, and storage areas.

The FabLabs established at KTU, ITU, and ISU emerged through the reorganization of space within the existing spatial layout of the architecture faculty. This constraint has led to the necessity of designing spaces within a certain area. However, research indicates that the area specially designed for the fab lab at METU has a larger area, leading to the emergence of a more specialized FabLab space.

Based on the findings, this research recommends:

- The educational requirements for advanced technologies, such as robotic fabrication applications at the undergraduate level, are disadvantageous in terms of time, effort, and cost. For this reason, it was found that the use of robotic tools and integration into the curriculum are rarely seen in undergraduate architecture courses.
- The current courses are predominantly didactic and introductory in nature, given the relatively short duration of the courses. Although these courses should facilitate an integration between theory and practice, as well as provide a creative environment for students, they tend to prioritize teaching the use of digital tools with generic and short exercises. In this context, the KTU curriculum is the most effective case due to its organized, sequential courses.
- The courses related to computational design are completed within the first two semesters, mostly as elective courses to build a strong foundation in digital design and fabrication techniques. However, it would be beneficial to integrate as mandatory courses with more advanced tools, such as robotics, into the curriculum in later semesters. In this context, IBUN is the most exemplary case of robotic integration attempts in the curriculum.
- Rather than allowing the curriculum to diverge from this foundational context, these advanced tools should be incorporated into the ongoing educational process through other mandatory courses. Elective courses could then focus on more specialized topics within a narrower scope, allowing students to develop expertise in specific areas of digital fabrication. Furthermore, the curriculum should include robotic fabrication technologies to prepare for the evolving demands of the architecture profession.
- The universities with digital fabrication laboratories do not typically have spaces designed systematically. Furthermore, robotic tools are employed more frequently for research purposes at post graduate level rather than undergraduate level, due to considerations related to security and pre-training needs. Therefore, it is recommended that the existing Fablab spaces should be expanded and specialised such as METU case. In addition, desktop robots that are more suitable for educational purposes, equipped with security sensors, require less space and are less costly should be utilized.

This research fills a gap in the literature by analysing the course content of architecture schools in Turkey regarding digital design and fabrication. It also documents how the students have undergone a spatial transformation to complement their course content. In this way, it shows the current situation of pioneer universities and provides an idea of how to develop them. Moreover, this research provides guidelines for other universities. This section discusses the requirements, potentials, and limitations of theoretical and practical training that should be included in these courses in the curriculum. On the other hand, it also shows the importance of empirical studies on incorporating these tools into education.

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