

MODELING AND ANALYZING THE DIGITAL EDUCATION SYSTEMS

(DİJİTAL EĞİTİM SİSTEMLERİNİN MODELLENMESİ VE ANALİZİ)

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LIST OF SYMBOLS

AHP	: Analytical Hierarchy Process
AHS	: Analitik Hiyerarşi Süreci
CEBOM	: Cross-Entropy-based Optimization Model
COCOSO	: Combined Compromise Solution
COPRAS	: Complex Proportional Assessment
ÇKKV	: Çok Kriterli Karar Verme
DEA	: Data Envelopment Analysis
DEMATEL	: Decision Making Trial and Evaluation Laboratory
DETI	: Digital Education Trustworthiness Index
DMs	: Decision-Makers
e-STEP	: Entropy Step
EDAS	: Evaluation based on Distance from Average Solution
FFDWPM	: Fermatean Fuzzy Dombi Weighted Partitioned Muirhead Mean
FFSs	: Fermatean Fuzzy Sets
HoQ	: House of Quality
KFG	: Kalite Fonksiyonu Göçerimi
MACONT	: Mixed Aggregation by Comprehensive Normalization Technique
MADM	: Multi-Attribute Decision Making
MARCOS	: Measurement of Alternatives and Ranking according to the Compromise Solution
MCDM	: Multi-Criteria Decision Making
MODM	: Multi-Objective Decision Making
PIPRECIA	: Pivot Pairwise Relative Criteria Importance Assessment
PMM	: Partition Muirhead Mean
PRISMA	: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSI	: Preference Selection Index
QFD	: Quality Function Deployment
STEAM	: Science, Technology, Engineering, Arts, Mathematics
SWOT	: Strengths, Weaknesses, Opportunities, Threats
TOPSIS	: Technique for Order Preference by Similarity to Ideal
TRs	: Technological Requirements
URs	: User Requirements
VIKOR	: VIseKriterijumsa Optimizacija I Kompromisno Resenje

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ABSTRACT

The healthy realization of social transformations is not only possible through industrial and technological transformations. In parallel, change and transformation in areas such as education and health, which will drive the basic dynamism of society, must also be carried out systematically. The widespread use of rapidly developing technologies in production has led to the current era being defined as Industry 4.0. With Industry 4.0, the social structure of societies has changed and this digital change has affected all institutions, leading to the emergence of concepts such as Health 4.0, Business 4.0, and Education 4.0. This rapid development has also brought about changes in the field of education. Accordingly, Education 1.0 was structured to focus on the needs of the agricultural society, Education 2.0 on the needs of the industrial society, Education 3.0 on the needs of the society shaped by globalization, and Education 4.0 on the needs of the innovative society.

The Education 4.0 approach is the vision of providing the capabilities and opportunities of new and evolving technologies, especially artificial intelligence, to meet the learning needs of students of all ages and strata in accordance with the rapid and comprehensive change of life. With this vision, instead of transferring the same content to individuals crowded into physical or virtual classroom space, quality, and customized content is offered to each individual according to their needs, and students can access this content from anywhere in the world, regardless of time. Education 4.0 is an approach that aims to maximize the use of digital technologies and open-source content. This approach to learning helps students to develop themselves according to changes in society and encourages students to develop the ability to apply new technologies. Approaches and technologies such as visual learning, personalized education systems, game and scenario-based learning, project-based problem solving, augmented reality, and artificial intelligence are used to provide students with these skills. Recently, digital education

opportunities have increased with developing technologies, and changes are being made in the education system to integrate individual and non-formal education methods in a single structure.

In addition, especially with the COVID-19 pandemic, change and transformation in education has become a necessity. During the pandemic period, these changes have accelerated and the use of digital environments has entered our lives to continue education remotely. In this context, the aim of this thesis is to increase the effectiveness of digital education with the models and approaches presented and to obtain better quality and effective outputs from digital education. In line with these objectives, firstly, a comprehensive literature review is conducted, academic studies, industrial reports, and books are examined and gaps in the literature are identified.

Based on the gaps in the literature, the existing digital education platforms are first evaluated and the most appropriate platform that can meet the needs in the digital education model is determined. In this context, the evaluation of digital education platforms, which incorporate many factors, is addressed with a MCDM approach.

Secondly, after evaluating the existing digital education platforms, a new technology-based digital education model is designed by considering future technologies. As a result of the detailed literature review, a metaverse-based digital education system is presented by integrating the Metaverse, which is seen as a continuation of educational platforms, into the digital education system using the House of Quality approach, which is a part of QFD. While creating this model, it is aimed to design a model that meets URs and is suitable for TRs. At the same time, this section evaluates the supporting digital technologies required for the metaverse-based education system.

Finally, the trustworthiness of the digital education system, which is a prominent issue when evaluating technologies in both structures, is examined. In this context, a trustworthy digital education system model is created and an index-based evaluation approach is presented for an existing digital education system to be trustworthy. Based

on the components of the model, a trustworthiness index for the digital education system is calculated and action plans are proposed accordingly.

In this thesis, all the approaches presented are supported by the fermatean fuzzy approach, as it is difficult for experts to evaluate and make decisions about the system when information is insufficient and uncertain. This approach facilitates the decision-making process of experts in complex and uncertain situations and provides them with a more realistic and flexible environment for evaluation.

In addition, the integrated fermatean fuzzy DEMATEL-MACONT approach that is used to evaluate digital education platforms, the QFD approach with fermatean fuzzy AHP method that is used to evaluate the metaverse-based education system, and the DETI index approach with fermatean fuzzy PIPRECIA method that is used to evaluate the trustworthiness of the system are proposed.

The proposed approaches have been applied to real case studies with the help of industrial experts' evaluations. The results are discussed and conclusions are drawn for an effective digital education system structure.

The contribution of this thesis to the literature is that it proposes several generic evaluation models of digital education systems and applies them to real cases. Another contribution is that many different approaches based on fermatean fuzzy sets are presented.

ÖZET

Toplumsal dönüşümlerin sağlıklı bir şekilde gerçekleşebilmesi sadece endüstriyel ve teknolojik dönüşümler ile mümkün değildir. Buna paralel olarak, eğitim ve sağlık gibi toplumun temel dinamiklerini yönlendirecek alanlarda da değişim ve dönüşümün sistematik bir şekilde yürütülmesi gerekmektedir. Hızla gelişen teknolojilerin üretimde yaygın biçimde kullanılması, içinde bulunduğumuz çağın Endüstri 4.0 olarak tanımlanmasına yol açmıştır. Endüstri 4.0 ile birlikte toplumların sosyal yapısı değişime uğramış ve meydana gelen bu dijital değişim tüm kurumları etkileyerek, Sağlık 4.0, İş 4.0 ve Eğitim 4.0 gibi kavramların ortaya çıkmasına neden olmuştur. Hızla devam eden bu gelişim, eğitim alanında da değişiklikleri beraberinde getirmiştir. Bu doğrultuda, Eğitim 1.0 tarım toplumunun ihtiyaçlarına, Eğitim 2.0 sanayi toplumunun ihtiyaçlarına, Eğitim 3.0 küreselleşme ile şekillenen toplumunun ihtiyaçlarına ve Eğitim 4.0 ise yenilikçi toplumun ihtiyaçlarına odaklanacak biçimde yapılandırılmıştır.

Eğitim 4.0 yaklaşımı, başta yapay zekâ olmak üzere yeni ve evrimleşen teknolojilerin yetenek ve imkânlarının, yaşamın hızlı ve kapsamlı değişimine uygun olarak her yaş ve katmandan öğrencilerin öğrenme ihtiyaçlarını karşılamak üzere sunulması vizyonudur. Bu vizyon ile fiziksel veya sanal bir sınıf mekânına dolmuş bireylere aynı içeriğin aktarılması yerine herkesin kendi ihtiyacına uygun kaliteli ve özel içerik sunulmakta ve bu içeriğe öğrenci, dünyanın herhangi bir noktasından zamandan bağımsız olarak erişebilmektedir. Eğitim 4.0, dijital teknolojilerden, açık kaynaklı içerikten en yüksek düzeyde yararlanmayı hedefleyen bir yaklaşımdır. Bu öğrenme yaklaşımı, öğrencinin toplumdaki değişimlere göre kendini geliştirmesine yardımcı olmakta ve öğrencilerin, yeni teknolojileri uygulama yeteneğini geliştirmelerini teşvik etmektedir. Öğrencilere bu yetenekleri kazandırabilmek için görsel öğrenme, kişiselleştirilmiş eğitim sistemleri, oyun ve senaryo tabanlı öğrenme, proje tabanlı problem çözme, artırılmış gerçeklik, yapay zekâ gibi yaklaşım ve teknolojiler kullanılmaktadır. Son dönemlerde, gelişen

teknolojiler ile birlikte dijital eğitim olanakları artmakta, bireysel ve yaygın eğitim yöntemlerinin tek bir yapıda bütünleştirilmesi için eğitim sisteminde değişikliklere gidilmektedir.

Buna ek olarak özellikle COVID-19 pandemisi ile eğitimdeki değişim ve dönüşüm bir zorunluluk haline gelmiştir. Pandemi döneminde bu değişiklikler hız kazanarak eğitimin uzaktan devam ettirilebilmesi için dijital ortamların kullanımı hayatımıza girmektedir. Bu kapsamda bu tezin amacı sunulan model ve yaklaşımlar ile dijital eğitimin etkinliği artırmak ve dijital eğitimden daha kaliteli ve etkili çıktılar elde etmektir. Bu amaçlar doğrultusunda öncelikle kapsamlı bir yazın taraması yapılarak akademik çalışmalar, endüstriyel raporlar ve kitaplar incelenmekte ve yazındaki boşluklar belirlenmektedir.

Yazındaki boşluklardan yola çıkılarak için öncelikle var olan dijital eğitim platformları değerlendirilmekte ve dijital eğitim modelinde ihtiyaca cevap verebilecek en kullanışlı platform belirlenmektedir. Bu kapsamda, birçok faktörü bünyesinde barındıran dijital eğitim platformlarının değerlendirilmesi Çok Kriterli Karar Verme (ÇKKV) yaklaşımı ile ele alınmaktadır.

İkinci olarak mevcuttaki dijital eğitim platformları değerlendirildikten sonra geleceğin teknolojileri düşünülerek teknoloji bazlı yeni bir dijital eğitim modeli tasarlanmaktadır. Yapılan detaylı yazın taraması sonucunda eğitim platformlarının devamı niteliğinde görülen Metaverse'ün dijital eğitim sistemine entegre edilmesi ile metaverse tabanlı bir dijital eğitim sistemi Kalite Fonksiyonu Göçerimi (KFG)'nin bir parçası olan Kalite Evi yaklaşımı kullanılarak sunulmaktadır. Bu model oluşturulurken kullanıcı beklentilerini karşılayan ve teknolojik gereksinimlere uygun olacak bir model tasarlamak amaçlanmaktadır. Aynı zamanda bu bölümde oluşturulan metaverse tabanlı eğitim sistemi için gerekli olan destekleyici dijital teknolojiler değerlendirilmektedir.

Son olarak her iki yapıda da teknolojileri değerlendirirken öne çıkan bir konu olan dijital eğitim sisteminin güvenilirliği (*trustworthiness*) incelenmektedir. Bu kapsamda kullanıcı odaklı güvenilir dijital eğitim sistemi modeli oluşturularak var olan bir dijital eğitim sisteminin güvenilir olması için indeks temelli bir değerlendirme yaklaşımı

sunulmaktadır. Oluşturulan modelin bileşenlerinden yola çıkarak dijital eğitim sistemi için bir güvenilirlik indeksi hesaplanmakta ve buna uygun olacak şekilde aksiyon planları önerilmektedir.

Bu tezde, sunulan tüm yaklaşımlar, bilginin yetersiz ve belirsiz olduğu durumda değerlendirme yapmak ve sistem ile ilgili karar vermek uzmanlar için zorlaşacağından fermatean bulanık yaklaşım ile desteklenmektedir. Bu yaklaşım, uzmanların karmaşık ve belirsiz durumlarda karar verme süreçlerini kolaylaştırmakta ve onlara değerlendirme yapmaları için daha gerçekçi ve esnek bir ortam sağlamaktadır.

Sunulan yaklaşımlara ek olarak dijital eğitim platformlarının değerlendirilmesinde entegre edilmiş fermatean bulanık DEMATEL yöntemi ile fermatean bulanık MACONT yöntemi; metaverse tabanlı eğitim yapısının değerlendirilmesinde fermatean fuzzy KFG yaklaşımı ile entegre edilmiş fermatean fuzzy Analitik Hiyerarşi Süreci (AHS) yöntemi; ve son olarak sistemin güvenilirliğinin değerlendirilmesinde dijital eğitim güvenilirlik indeksi yaklaşımına entegre edilmiş fermatean fuzzy PIPRECIA yöntemi kullanılmaktadır.

Önerilen yaklaşımlar, endüstriyel uzmanların değerlendirmeleri alınarak gerçek vaka analizleri üzerinde uygulanmıştır. Elde edilen sonuçlar tartışılmış ve etkin bir dijital eğitim sistemi yapısı için final çıkarımlar yapılmıştır.

Bu tezin yazına katkısı, dijital eğitim sistemi ile ilgili jenerik birçok model önermesinden ve bu modelleri gerçek vakalara uygulamasından kaynaklanmaktadır. Bir diğer katkı ise, fermatean bulanık kümelerle dayalı birçok farklı yaklaşım sunulmasıdır.

1. INTRODUCTION

Social transformations cannot be realized in a healthy way only with industrial and technological transformations. In parallel with these transformations, it is necessary to carry out change and transformation in a systematic way in areas that will direct the basic dynamism of society, such as education and health. In addition to the economic developments that occurred with the Industrial Revolution, information technologies also entered an important development process (Bilyalova et al., 2019; Ishak & Mansor, 2020). This rapid development and change has brought global competition and cooperation and has played a major role both in the daily lives of individuals and in the process of creating a digital society.

With the COVID-19 pandemic all over the world, change and transformation in education is a necessity. Distance education is no longer a choice but a necessity. The rapid transition to distance education during the COVID-19 pandemic has naturally brought many problems. Lack of adequate infrastructure, lack of specialized personnel in the field, lack of content, and most importantly, the lack of adequate readiness of learners and teachers. These problems also affect the perception of distance education. However, it is possible to encounter similar problems and complaints in face-to-face education environments. It is necessary to see digital education as a method and use it to meet our needs and continue on our way by completing its deficiencies.

The widespread use of rapidly developing technologies in production defines the current age as Industry 4.0. With Industry 4.0, the social structure of societies has changed, and this digital change has affected all institutions, causing the emergence of concepts such as Health 4.0, Government 4.0, and Education 4.0. This rapid development has brought about changes in the field of education (Bilyalova et al., 2019). In this direction, Education 1.0 is structured to focus on the needs of the agricultural society, Education

2.0 is structured to focus on the needs of the industrial society, Education 3.0 is structured to focus on the needs of the society shaped by globalization, and Education 4.0 is structured to focus on the needs of the innovative society (Puncreobutr, 2016; Hussin, 2018).

The Education 4.0 approach is the vision of presenting the capabilities and opportunities of new and evolving technologies, especially artificial intelligence, to meet the learning needs of students of all ages and layers in accordance with the rapid and comprehensive change of life (Butt et al., 2020; Ishak & Mansor, 2020). With this vision, instead of transferring the same content to individuals occupied in a physical or virtual classroom space, quality and special content suitable for everyone's needs is offered, and the student can access this content from any point in the world, regardless of time.

Education 4.0 leverages digital technologies, open-source content, and connectivity at the highest level. This learning approach helps students develop themselves according to changes in society and encourages students to develop their ability to apply new technologies (Puncreobutr, 2016; Butt et al., 2020). Approaches and technologies such as game and scenario-based learning, visual learning, project-based problem-solving, personalized education systems, augmented reality, and artificial intelligence are used to provide students with these abilities. Recently, with the developing technologies, distance education opportunities have been increasing, and there have been changes in the education system to integrate individual and non-formal education methods in a single structure (Butt et al., 2020, Teng et al., 2023).

The motivation for this thesis is the necessity to make changes in the field of education due to the COVID-19 pandemic and the desire to offer a digital education system that provides quality and efficient results. In this context, the main objectives of this thesis are to increase the effectiveness of digital education and provide a digital education system framework with better quality and efficient outcomes.

The sub-objectives of this thesis are as follows:

- to provide a structured overview of Education 4.0, a taxonomy and review of the concept of Education 4.0, and a definition of Education 4.0
- to assess existing digital education platforms to determine the most appropriate platform that meets user expectations
- to propose a design system for metaverse-based education with QFD approach based on user requirements (URs) and technological requirements (TRs) and evaluate digital technologies for integration into this form of education
- to propose index-based evaluation approach for trustworthy digital education system to be ethical, beneficial, responsible, explainable and fair

In line with these objectives, the scope of the thesis are established as shown in Figure 1.1. Firstly, in Chapter 2, a detailed literature review process has been conducted. The historical change and development of the education system are examined and the definitions of technology-based education systems are discussed. Based on these, the definition of Education 4.0 is made and the characteristics of Education 4.0 are analyzed. Through a detailed literature review, scientific studies, sectoral reports, and books are systematically examined and gaps in the literature are revealed based on these sources.

Following the results of the literature review, it is first necessary to utilize digital education platforms to realize digital education. In this context, this thesis presents a model consisting of user expectations that will enable the evaluation of digital education platforms. The proposed models in the evaluation approach of the thesis study and the analysis process of these models are parts of a decision-making process based on expert opinions and they include many criteria. Hence, Multi-Criteria Decision Making (MCDM) methods are adopted to the stages of the thesis by considering their wide range of usability. However, it becomes difficult for decision-makers (DMs) to evaluate and make decisions about the system with numbers when the information is insufficient and uncertain (Zadeh, 1996). So, employing the fuzzy sets may not deal with human perception, hesitation, and intuition. For this reason, in this study, the fermatean fuzzy sets (FFSs) are used to assess the MCDM problem more realistically and flexibly (Senapati & Yager, 2019).

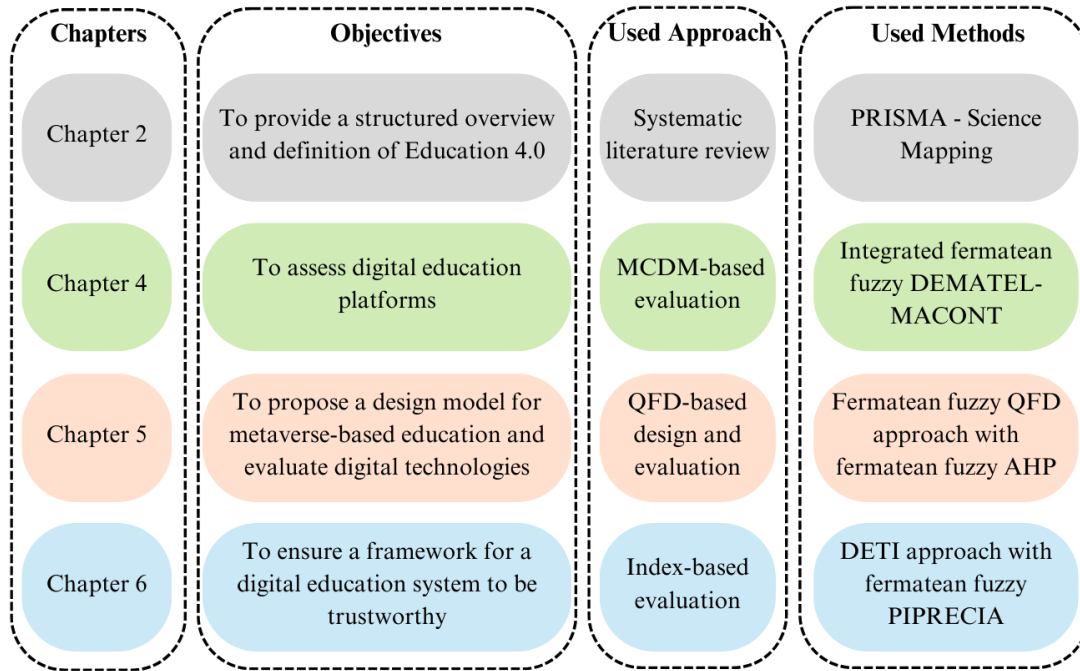


Figure 1.1: Thesis scope

FFSs are a generalization of intuitionistic fuzzy sets and pythagorean fuzzy sets that are more flexible and efficient in dealing with uncertain and ambiguous information in real-life applications because the sum of cubes of membership and non-membership degrees are considered during the evaluation process. The main advantage of FFS is that it gives experts more flexibility to express their views and opinions than other approaches (Senapati & Yager, 2019; Senapati & Yager, 2020).

In this context, in Chapter 4, the user expectations of these platforms are collected and the weights of these expectations are calculated with the fermatean fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) method. Thanks to this method, the relationships between expectations are taken into consideration. Afterwards, digital education platforms are evaluated using the fermatean fuzzy Mixed Aggregation by Comprehensive Normalization Technique (MACONT) method. In this way, results that will increase the quality and efficiency of education have been obtained.

Secondly, after identifying the most appropriate digital education platform to improve the quality of the outcomes of the existing digital education system in the previous

chapter, a digital education system focusing on Metaverse, one of the digital technologies of the future, is designed in the Chapter 5. Based on URs and TRs, a design is structured for metaverse-based education. Quality Function Deployment (QFD) is used to design this problem. QFD is a competent way to improve systems based on URs by translating them into appropriate TRs (Bottani & Rizzi, 2006). In this methodology, the QFD's first phase (i.e. House of Quality (HoQ)) is applied. To achieve an efficient HoQ, this tool is integrated with a fermatean fuzzy MCDM approach. The HoQ matrix is a tool that determines the URs. These URs, which are determined by literature review and expert opinions, should have importance degrees for the evaluation of TRs. In this study, the importance of URs is calculated with fermatean fuzzy Analytical Hierarchy Process (AHP) technique. In addition, this technique is integrated with aggregation operators. These operators greatly increase the flexibility of the integrated method in the evaluation process.

Finally, these digital education systems should provide a certain level of trust in terms of content. One of the most important constraints related to digital transformation is the creation of trustworthy infrastructures. To achieve this, Chapter 6 presents an index-based evaluation approach for the trustworthy digital education system. The trustworthiness of the system is measured by an index-based evaluation approach. While calculating digital education trustworthiness index (DETI), the fermatean fuzzy Pivot Pairwise Relative Criteria Importance Assessment (PIPRECIA) method is used to calculate the weights of the components. In addition, action plans are proposed according to the obtained index values.

The rest of the thesis is structured as follows: The following chapter presents a literature review on digital transformation in education. Chapter 3 presents the methodological background for used approaches, used technique, used methods, and computational steps of the proposed approaches. Following this, the evaluation of digital education platforms is given in Chapter 4. Chapter 5 gives the proposed metaverse-based education system with QFD approach. The proposed index-based evaluation approach for trustworthy digital education system is presented in Chapter 6. Finally, Chapter 7 presents the conclusions of the thesis and future works.

2. LITERATURE REVIEW ON DIGITAL TRANSFORMATION IN EDUCATION: EDUCATION 4.0

The main methodology and initial findings of this chapter can be found in this article. (Mukul & Büyüközkan, 2023). This chapter provides an updated version of the article and more detailed analysis. In this chapter, the digital education approach is first explained conceptually and then the studies obtained as a result of the literature research are analyzed through the classification methodology.

The overall review methodology for digital education is graphically presented in Figure 2.1.

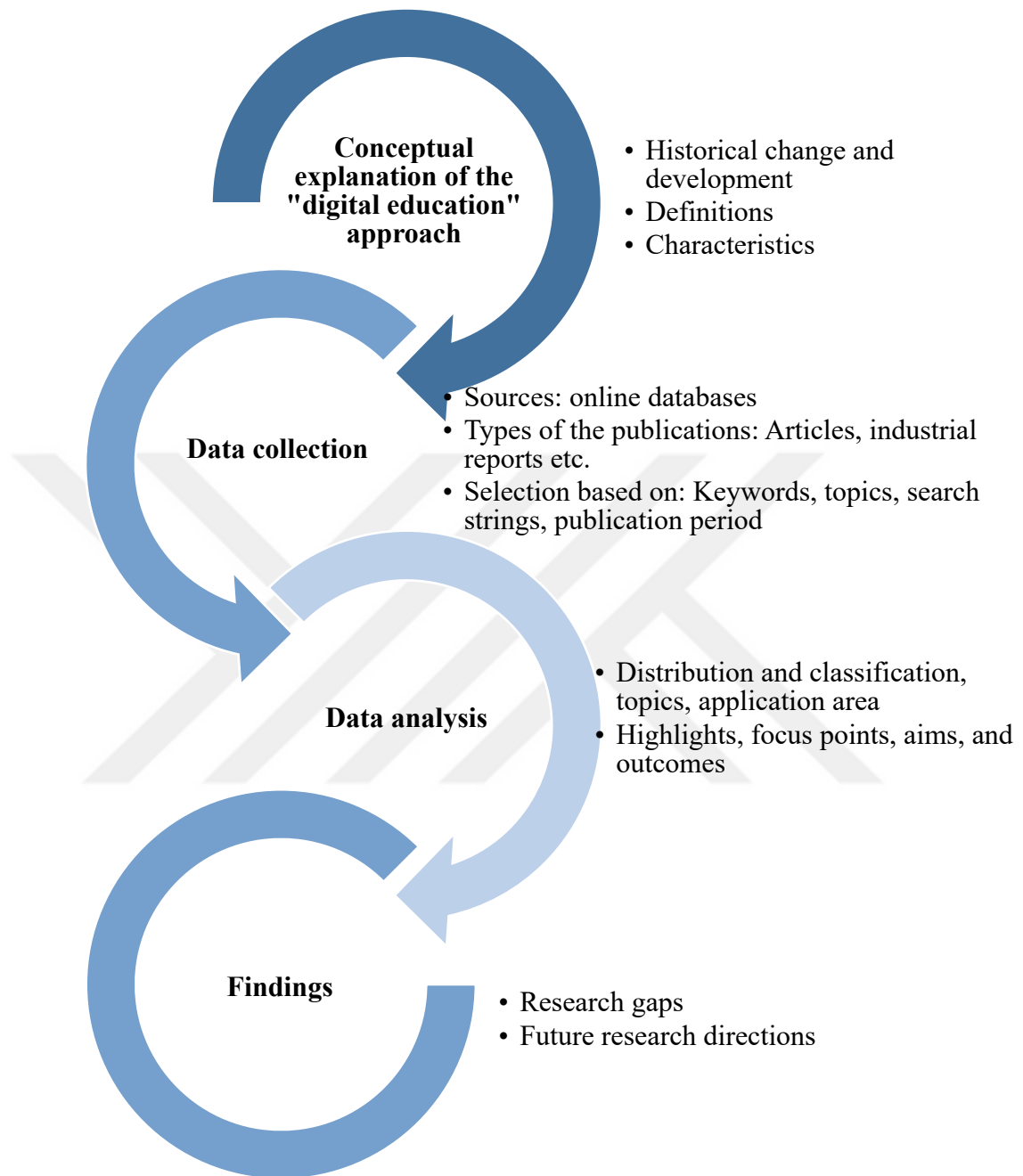


Figure 2.1: The flowchart of the review methodology

2.1. Historical Change and Development of the Education System

Social transformations nowadays need elements beyond only industrial and technological progress. Systematic execution of change and transformation is also essential in education and health to guide the basic dynamism of a society (Sharma, 2019).

Economic developments have been occurring thanks to the revolution in the industry, information, and communication technologies. This rapid development has been playing a major role both in the daily life of individuals and in the process of creating a digital society (Puncreobutr, 2016). Compared to previous social constructs, this emerging digital society is defined by a completely new perception of time and place and virtually unlimited access to information. With the widespread use of rapidly developing science and technology in production technologies, the current age is called Industry 4.0. Its applications are framed as "X4.0" with an increasing need for transdisciplinary considerations in parallel with the developments in the sectors and technology (Beckett & Daberkow, 2019; Mo & Beckett, 2022), leading to the emergence of accompanying concepts such as Health 4.0, Business 4.0, Education 4.0, and Manufacturing 4.0 (Ashaari et al., 2021).

Industrial changes and revolutions in the production sector have affected the structures and institutions of societies in every field from the past to the present. Educational institutions are being restructured to equip the workforce with the necessary skills required in industry and society (Margulieux et al., 2016). The term historically progressed in a continuum: Industry 1.0 is defined by mechanization, water, and steam power; Industry 2.0 is defined by mass production, assembly line, and electricity; Industry 3.0 is defined by the computer and automation; and Industry 4.0 is defined by cyber-physical systems and data-driven analytics (Ashaari et al., 2021). This progress also brings a similar transformation in education: Education 1.0 is structured to focus on existing needs in the agricultural community, Education 2.0 on the needs of the industrial community, Education 3.0 on the needs of the society shaped by globalization, and Education 4.0 on the needs of the innovative society (Mohd Adnan et al. 2019).

In the Education 1.0 framework, information is simply transferred from teacher to student; the student receives information passively. Education 2.0 responds to the needs of the industrial society with the concept of "teaching technology". In Education 2.0, individuals are not seen as having the ability to distinguish themselves from others; each individual has similar qualities. Education 3.0 aims to find a solution to the needs

of the developing technology society. It promotes the production of knowledge by supporting self-learning. In this period, education focuses on interactive learning by using learning materials in digital and social media formats (Salmon, 2019).

Education 4.0 supports individuals to keep up with the innovative age. This learning method helps the student to improve himself according to contemporary changes in society, encouraging students to develop the applicability of new technologies. Today, there is an imperative for lifelong learning and self-improvement. For this reason, Education 4.0 is much more than just formal education (Chakraborty et al., 2023).

Education 4.0 is beyond the traditional education system. It is rather a learning process based on 3 features (Puncreobutr, 2016):

- Regulating understanding 3R (Recalling, Relating, Refining)
- Triggering research 3I (Inquiring, Interacting, Interpreting)
- Being result-oriented 3P (Participating, Processing, Presenting)

From a conceptual perspective, the Education 4.0 vision has three main features (Hussin, 2018):

- “Smartness” that emerges as a result of the access of information technology to high speed and high volume data processing capacities and artificial intelligence applications gaining new opportunities;
- “Connectivity” linking almost the whole world and objects with the development of wired and wireless connections, local networks, and the Internet; and
- "Real-time" created by advances in sensor and data acquisition technologies.

Education 4.0 refers to the future design and vision of learning. It aims to utilize digital technologies, personalized data, open-source content and connectivity at the highest level. It ensures that the society and the individual have better living conditions and opportunities under the understanding of sustainability of life. Education 4.0 aims to

develop individuals to be creative and innovative. In Education 4.0, 21st-century skills are needed such as cooperation, creativity, leadership, effective communication, entrepreneurship, teamwork, global citizenship, and problem-solving. Following this, it is essential to encourage people to use new approaches and technologies such as smart agents, mobile technologies, and cloud computing (Benešová & Tupa, 2017; Yi & Tan, 2023).

Passing these skills onto students requires methods such as personalized education systems, visual learning, project-based problem-solving, game- and scenario-based learning, and augmented reality (Núñez-Canal et al., 2022). Education 4.0 reflects the educational preferences and habits of Generation Z students. Integrating up-to-date technologies into education will enable instructors to be more creative in designing lessons. Thus, students of this generation, whose attention span is the most limited of any modern generation, will be able to participate effectively in lessons, thanks to engaging learning materials.

The Education 4.0 vision focuses on an emergent future. It places the individual at the core of its focus and aims to equip it with the skills that meet the needs of the 4.0 ecosystem, with all its personalized products and services for the present and the future.

The historical development of the education system is depicted in Figure 2.2. The first industrial period in the 18th century was still dominated by an agricultural economy and was based on mechanical production equipment powered by water and steam power. In this period, education was built on the memorization of experience accumulated for centuries.

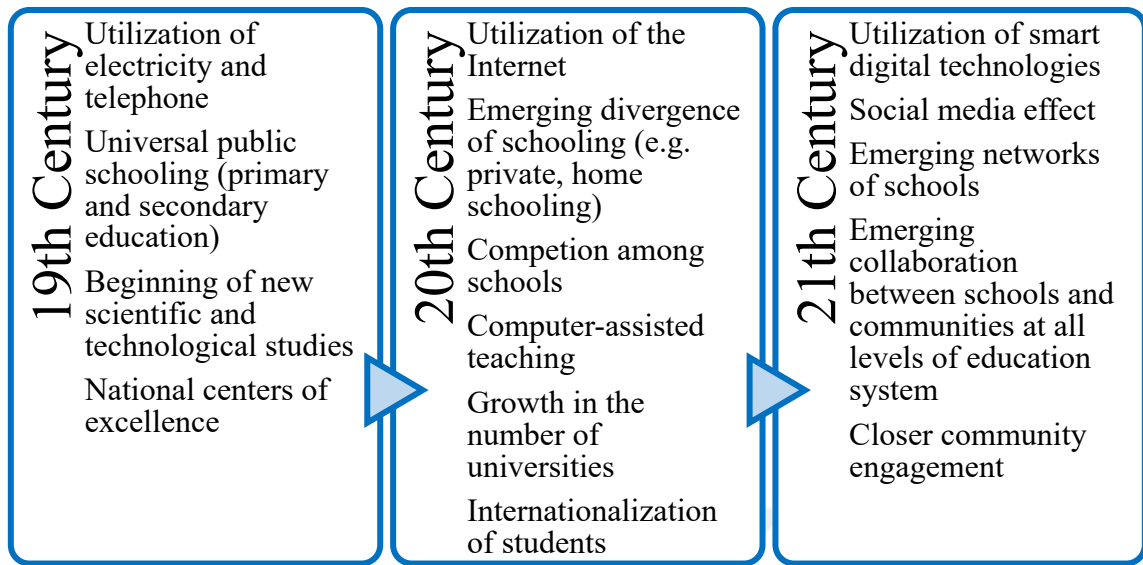


Figure 2.2: Historical development of the education system (Jeschke, 2014; Hew & Cheung, 2014; Margulieux et al., 2016; Mhlana & Moloi, 2020; Hashmi et al., 2021; Chakraborty et al., 2023)

The second industrial age emerged in the late 19th century and was focused on mass production. Among the main features of this period was the use of electricity in industry. Although new scientific and technological developments emerged in this period, the effects of traditional education have remained. Living standards and average income improved with economic growth; and with the introduction of universal public education, more people began to benefit from the achievements of the industrial revolution. However, schooling was modeled to respond to social labor demand. In mass education, a teacher taught as many students as possible with standardized content. Thus, the curriculum model that met the demands of the labor market was static, linear, and standardized (OECD Report, 2019).

In the first half of the 20th century, the world experienced two wars of a scale never before seen. Military interests and priorities have led to the emergence of computers. These computers became part of industrial benches, later to be accelerated with the advent of the Internet. Especially with the widespread use of personal computers, studies and experiments on computer-aided education started to attract attention. In this

Education 3.0 period, technology started taking its first steps in the field of education (Pooworawan, 2015; Hussin, 2018).

Since 2010, the phenomenon of cyber-physical systems together with technologies such as artificial intelligence, big data, augmented reality, mobility, autonomous robots, fast and widespread Internet have been defining the world. This educational vision is shaped by the focus on creating innovation. Schools aim to work with a curriculum that acknowledges the need for interdependence and expands the objectives of education to include "education for citizenship". For this reason, they need to be more flexible and personalized to enable each student to realize their unique talents and fulfill their potential (Margulieux et al., 2016; OECD Report, 2019).

Table 2.1: Traditional education system vs. education system in the “new normal” (Hew & Cheung, 2014; Janíková & Kowalikova, 2017; Hussin, 2018; Butt et al., 2020)

Traditional education system	Education system in the “new normal”
• Education system is a separate organization	• Education system is a portion of a bigger eco-system
• Labor division (Directors manage schools, instructors teach, students listen to instructors and learn)	• Shared accountability (everyone works together and takes responsibility and students have the responsibility for their own learning)
• Outputs are used to evaluate the effectiveness and quality of school experience.	• Not only “outcomes” but also "process" is used to measure the effectiveness and quality of the school experience.
• The standardized model	• The personalized model
• Standardized testing for student assessment	• Various types of assessments used for various purposes of student assessment
• Learning by listening to instructor’s guidance with increasing student autonomy	• Committed participant, both with the student agency and with the instructor agency in particular

Education 4.0 represents a period in which skills become increasingly prominent. It utilizes new technologies, such as artificial intelligence, to meet the learning needs of students of all ages and layers. It touches all the elements that make up an educational institution and system. One of the most important features of this change is the provision of quality and special content that is suitable for everyone's own needs, instead of transferring the same content to each individual, be it in a physical or virtual classroom space. Education 4.0 aims not to store information in students, but instead give them the skills to make sense and use of that readily available information. The differences between the traditional education system and the new normal education system are shown in Table 2.1.

2.2. Definitions of Technology-based Education System Terms

In the literature, there are many terms for technology-based education, such as online education, mobile education, digital education, and smart education. These are not exactly the same concepts. Table 2.2 shows the descriptions of technology-based education terms. For a qualified literature review, Education 4.0 is defined here as follows:

Education 4.0 is an approach that is personalized to create innovative forms of learning using up-to-date technology that encourages students to access emerging devices at anytime, anywhere and on any device, and interact with different materials according to their skill and academic standards. Cloud computing, big data, and learning analytics, which concentrate on how to collect, interpret, and improve learning data to enhance learning and teaching, promote the advancement of customized and adaptive learning.

Table 2.2: Definitions of technology-based education terms

Terms	Definitions
Online education, Internet-based education	• Online education is defined by separating teachers and learners from face-to-face teaching, using a computer network that provides two-way communication to display or distribute any educational content (Volery & Lord, 2000).
Mobile education	• Learning through connections with personal electronic devices such as mobile phones, notebooks, iPads etc. (Newhouse et al., 2006).
Digital education	• Digital education is the process of learning and teaching through digital technology. It is an overarching concept for a growing plurality of methods, concepts and technologies to education. Digital education modalities range from the simple conversion of content into a digital format to the complex deployment of digital technologies (Williamson, 2016).
Smart education	• Smart education is an educational framework focusing on creativity that encourages students to learn using up-to-date technologies and work with different materials depending on their skills and academic ability (Zhu et al., 2016).

Table 2.2: Definitions of technology-based education terms (*continue*)

Education 4.0	• Education 4.0 addresses society's needs in an 'innovative era'. It is associated with the evolving technology with the special parallelism, synchronization, and simulation characteristics (Puncreobutr, 2016). • Education 4.0 is a virtual course with an interactive experience in the context of integrated learning and AI-driven technologies as major instructional technology challenges (Ciolacu et al., 2017b). • Education 4.0 discusses, on the one hand, the use of emerging technologies to promote the teaching process, and, on the other, the approaches and seminars that will familiarize young engineers with these technologies, as they will work in Industry 4.0 environments (Mourtzis et al., 2018). • Education 4.0 is born from educational theorists' observation that the Fourth Industrial Revolution will bring a new wave to the world, and will have a major influence on not just the economy, but also on education (Ishak & Mansor, 2020). • Education 4.0 is described as a school of thought that motivates non-traditional thinking amongst learners (Butt et al., 2020). • Education 4.0 is a learning framework that strategically includes capabilities (Chakraborty et al., 2023).
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2.3. Characteristics of Education Systems

The current education system has witnessed four phases in its transformation. Table 2.3 summarizes the core differences between these four generations of education (Hew & Cheung, 2014; Wallner & Wagner, 2016; Puncreobutr, 2016; Janíková & Kowalikova, 2017; Milićević et al., 2021).



Table 2.3: The characteristics of education systems

Characteristics	Education 1.0	Education 2.0	Education 3.0	Education 4.0
Goal	Process-based	Exhibitor-based	Skill-based	Human-based
Teachers	There are licensed instructors who are seen as a source of information.	They are licensed guides who team up with students, families, and other individuals.	They are guides in the creation of collaborative knowledge.	They are the source of innovation and production supported by learning portals and software "partners" anywhere and anytime.
Students	They are basically listeners.	They take part in their own learning responsibility and participate more actively.	They have their own learning plan and come up with new ideas, products.	They are autonomous and develop their education plans with the help of virtual platforms and guides, while adapting to constantly updated mechanisms.
Technology	There is an e-learning management system limited to a specific organization.	The use of technology has been carefully and cautiously adopted.	Technology has been used for the production and transmission of information that exists everywhere.	With web-based e-learning applications and the contributions of students, information is constantly updated.

Table 2.3: The characteristics of education systems (*continue*)

Location	They are fixed buildings where teaching and assessment are carried out by a single institution.	There is one-to-one communication between institutions and students, with collaboration between institutions.	It has penetrated into the society: cafes, parks and workplaces are perceived as learning centers.	These are timeless and spatial environments where regional and international borders disappear and all educational levels are supported.
Teaching	Direct presentation from the teacher to the student is done through written and oral tests and homework.	It is carried out from instructor to student and from student to student; Internet resources are a natural part of the learning.	Social networks provide relationships across disciplines, institutions and international borders, and open learning activities.	Teaching and learning can be carried out creatively in every area of life, 24 hours a day, 7 days a week.
Content Arrangements	Traditional copyright materials	Copyright and free/open learning opportunities for students within the discipline	Free/open learning opportunities developed and reused by students	User-generated content; DIY content; personalized content
Teaching & Learning mode	Pedagogy	Andragogy	Heutagogy	Cybergogy, Peeragogy
Learning Theory	Instructivism, behaviorism	Cognitivism	Constructivism	Connectivism

Technology-supported transformations have been continuous, i.e. each development supports the previous generation in Table 2.3. Previous generations did not completely disappear and were not fully replaced. Although some characteristics develop and change completely, certain changes have been iterative, thus carrying over some characteristics of the previous generation (Wallner & Wagner, 2016; Mhlanga & Moloi, 2020; Milićević et al., 2021).

2.3.1. Education 1.0

Education 1.0 is characterized by one-way communication between teachers and students, the teacher acting as a source of information. Information is conveyed comprehensively from teacher to student through concepts (Puncreobutr, 2016). Education 1.0 period, which focuses on traditional disciplines such as mathematics, history, natural sciences, literature, and foreign language learning, is shaped by an understanding of traditional assignments and assessment methods and isolated group studies. Web tools, if any, are used only for information transfer and are under the control of a limited number of information producers, and are closed to external interference.

In the period of Education 1.0, students have become individuals who consume the information given to them, rather than producing original products or new information, even if they perform activities using different resources available to them. In higher education institutions where the student is seen as an apprentice and where learning takes place unilaterally through knowledge transfer, academics are also defined as authoritative experts (Wallner & Wagner, 2016).

The main features of the concept of Education 1.0 are as follows (Pooworawan, 2015; Ciolacu et al., 2017a):

- Authoritative
- Students are passive beneficiaries

- Teacher-centered system – the teacher takes information as a leader in the classroom
- In-class technology is prohibited

2.3.2. Education 2.0

Education 2.0 starts with the transition to a new education system that provides the information and innovation needed for industrial societies of the 21st century. In other words, it was created by using Web 2.0 technologies such as blogs and podcasts in education. Education 2.0 still focused on the concept of teaching rather than engaging or creativity and was used only as a tool in the technology-learning process (Puncreobutr, 2016).

Education 2.0 is situated in an age of communication, creation, and contribution. In addition to the classroom as the learning environment, technology providers such as Google, Wikipedia, and WordPress provided students with the opportunity to conduct research and gather information from different sources. The instructor concept has changed; teachers are seen as both a source of information and a guide. Students become more active in terms of participation by taking on their own learning responsibilities. Although traditional assignments and activities continue, collaborative approaches are increasingly used (Núñez-Canal et al., 2022).

Online resources in higher education gained acceptance in Education 2.0, with the spread of blogs, wikis, and sharing sites. Web 2.0 technologies have been integrated into learning environments to develop traditional learning approaches and open educational resources with more variety in content, providing more information to students. In higher education institutions, students are accepted as receiving information, and academics are assistants who support learning (Margulieux et al., 2016).

The main features of the concept of Education 2.0 are as follows (Pooworawan, 2015; OECD Report, 2019):

- Growing communication and collaboration
- Examination-based method
- Knowledge memorization
- An underutilized student-centered approach

2.3.3. Education 3.0

Education 3.0 offers various possibilities for educational content shaped by technological elements according to the preferences of the users. The learning environments at this stage mostly focus on contextual information and texts supported by sound and image. Education 3.0 contains rich and multicultural education opportunities. Students not only have more responsibility for learning by their own, but do also generate new knowledge. The widespread use of internet networks and personal computers enables students to easily access the information they need. Constructivist learning, which allows the student to participate actively, has gained importance in the learning process. Local, regional, and international cooperation has become important in educational institutions and training content has been prepared accordingly (Hussin, 2018).

In this period, computer-aided and mutually interactive education systems emerge. Another important transformation that occurs during this period is that students are trained as “producers of knowledge” rather than those who only consume information. At this stage, ensuring the quality assurance of education systems is essential.

The main features of the concept of Education 3.0 are as follows (Mohd Adnan et al., 2019; OECD Report, 2019):

- Student-focused approach
- The instructor is turned into a coordinator / facilitator, counselor, learner and guide to practice
- The student explores and self-learns
- More dialogue

- The traditional style classroom is no longer seen as sufficient
- Lesson plans are now considered learning plans

2.3.4. Education 4.0

Education 4.0 is a modern educational method focused on the experience that uses emerging technologies instead of a memorized system. It responds to the demands of today's world with personalized education. This system, which envisages educating new generations to fulfill the demands of the Industry 4.0 future, brings technology, individuality, and exploratory learning into our lives.

Visualized education and training tools are used extensively in an Education 4.0 environment. In this period, “lifelong learning” is among the basic missions of educational institutions. Developing skills such as collaboration, leadership, entrepreneurship, creativity, effective communication, sensory intelligence, global citizenship, teamwork, and problem-solving skills are learning outcomes. In this sense, Education 4.0 is not only an education system. It trains people to feel and define world problems correctly (produce critical thinking), to produce innovative ideas for their solution (creative thinking), and to use the right methods and techniques for such solutions (scientific and analytical thinking) (Ciolacu et al., 2017b).

The main features of the concept of Education 4.0 are as follows (Jeschke, 2014; Ishak & Mansor, 2020):

- Co-creation and innovation-based system
- Maximum use of classroom applied interactive practical training
- Schooling takes place at home or outside school, while learners acquire skills in classrooms
- Designing personalized teaching and learning
- Learning plans are now called creativity plans
- Easily available technology
- Increased utilization of virtual reality

- Innovation and continuous growth

2.4. Data Collection

The overarching research question for this study is: to what extent do the changes (personalized education, flexible education system, etc.) in the Education 4.0 process that emerged with the development of current technology affect students' success and learning ability?

To address this question, the following three sub-research questions have been formulated to help us in carrying out the literature review and in achieving the research goals:

- (RQ1) What are the characteristics of the Education 4.0 concept as supported by digital technologies in the provision of a quality and sufficient education environment?
- (RQ2) Is it possible to create modules suitable for all users in an Education 4.0 framework and how much are users expected to benefit from this approach?
- (RQ3) Which digital technologies are used in Education 4.0 applications and which of these technologies is the most efficient for users?

The systematic review focused on the concept of Education 4.0. The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) (Moher et al., 2009) guidelines have been followed in the development of this paper.

Three databases are searched, namely Web of Science (WoS), ScienceDirect, and Scopus between. In the WoS database, the search was done with the specified keywords as Topic (with field tag “TS”). In the ScienceDirect database, the search was done with the specified keywords. In the Scopus database, the search was done with the specified keywords as “TITLE-ABS-KEY” and the search was refined to show only articles. Table 2.4 shows the search results and papers included for each database.

Table 2.4: Search results and articles selected per database (with keyword “Education 4.0”)

Database	WoS	Science Direct	Scopus
Results	157	90	106
Articles selected	61	23	45

The keywords used for the searches were “Education 4.0”. To be more inclusive, a second search was conducted with different keywords, the results of which are listed in Table 2.5.

The “Education 4.0 related” keywords (with tags) used when searching in the WoS database are as follows:

- TI=((“digital technology” AND education) OR (“digital transformation” AND education))
- Refined by: PUBLICATION YEARS: (2023 OR 2022 OR 2021 OR 2020 OR 2019 OR 2018 OR 2017) AND LANGUAGES: (ENGLISH) AND DOCUMENT TYPES: (ARTICLE)
- Indexes=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI Timespan=All years

The “Education 4.0 related” keywords used when searching in the ScienceDirect database are as follows:

- Title abstract, keywords: (“digital technology” AND education) OR (“digital transformation” AND education)
- 2017 and later were taken as the year filter. The language option was English. Document type was determined as article.

The “Education 4.0 related” keywords used when searching in the Scopus database are as follows:

- TITLE (("digital technology" AND education) OR ("digital transformation" AND education)) AND (LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017)) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar"))

Table 2.5: Search results and final articles selected per database (with “Education 4.0 related” keywords)

Database	WoS	Science Direct	Scopus
Results	218	232	265
Articles selected	49	56	52

To identify highly relevant articles addressing research questions, criteria were established for the inclusion and exclusion of articles. This research has been limited to English language journal publications on the topic of the identified keywords, with all studies being related to the concept of Education 4.0. Studies using digital technologies in education and dealing with digital transformation in education have been included in this research. All articles collected at the stages of the selection process were filtered according to these criteria. Table 2.6 summarizes the inclusion and exclusion criteria.

Table 2.6: Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Relevant to search and published from 2017 until 2023	Outside period of coverage
Listed in the preferred databases	Non-English
Full-text articles	Unavailable full text
Paper written in English	Duplicated studies

The study selection process made within the scope of the determined inclusion and exclusion criteria (with the keyword “Education 4.0”) was as in Figure 2.3. The WoS database searches resulted in 157 records, of which 2 were duplicates with 155 articles

remaining. After the English language selection, 142 studies remained, and abstracts were screened for eligibility. At this stage, 81 studies were excluded because of not article. Finally, 61 studies were included in the final review.

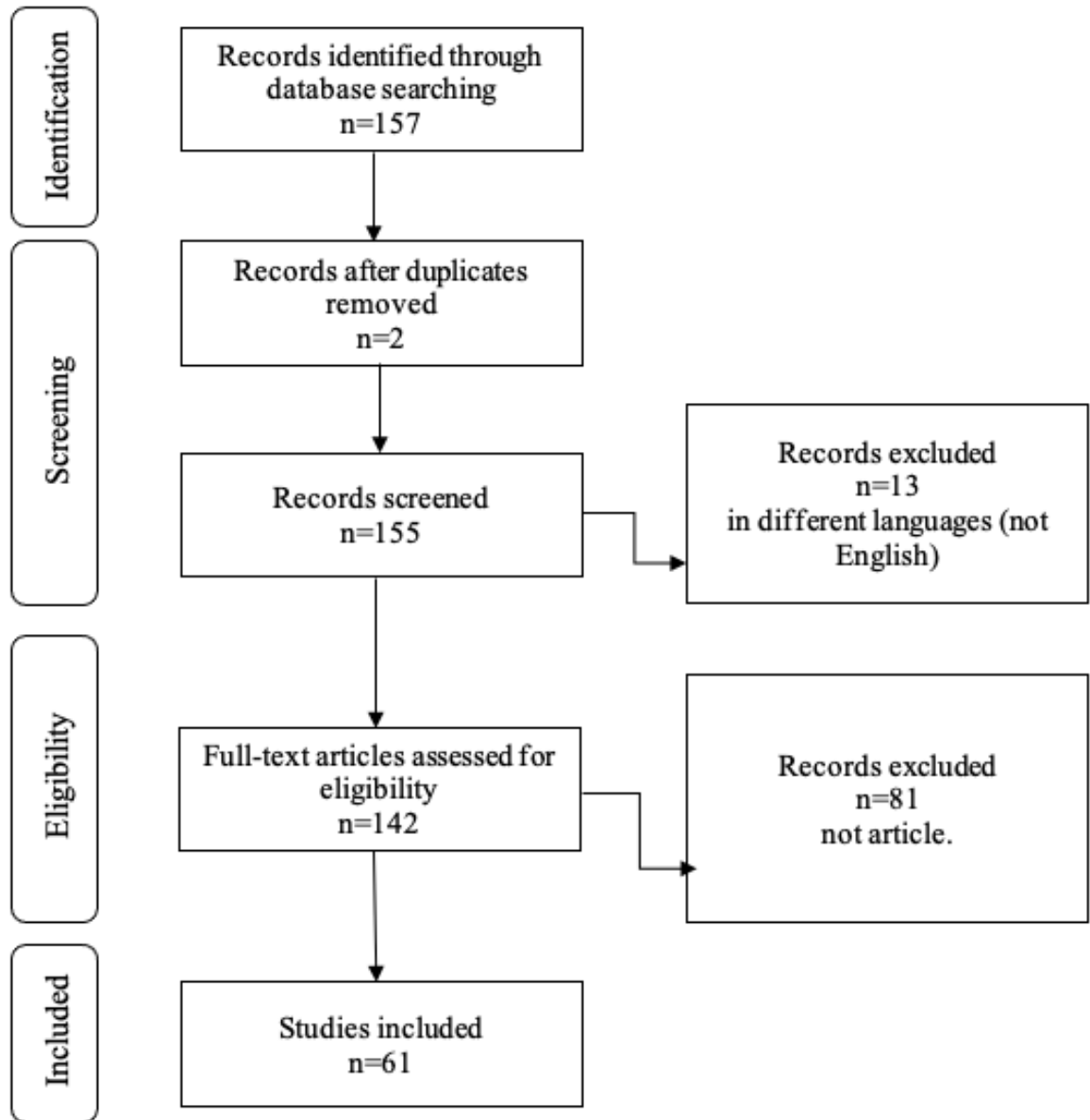


Figure 2.3: A diagrammatic representation of the PRISMA review process

When searching with the “Education 4.0 related” keywords, 218 studies were found in the WoS database with the title (TI) tag. To compare the results obtained when searching with the keyword "Education 4.0", the same filters were also used when searching with the keywords "Education 4.0 related". Studies conducted in 2017 and

after have been included. The document type is selected as article, and the language option is selected as English. Eventually, 49 studies were included in the final review.

2.5. Data Analysis

2.5.1. Papers Concerning “Education 4.0” Keyword

In this study, “Education 4.0” was searched as the topic (with the field tag “TS”) in the WoS database and 157 studies were found. Finally, after the selection process, 61 studies presented between 2017-2023 were examined, as shown in Table A.1.

2.5.2. Papers Concerning “Education 4.0 related” Keyword

In this part, the search was made using the following filters: TITLE (("digital technology" AND education) OR ("digital transformation" AND education)) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017)) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar")).

Table A.2 shows 49 articles determined by the selection process as a result of the search made with "Education 4.0 related" keywords. The comparison and analysis of these two search results will be explained in the following sections.

2.6. Review Results

In this thesis, a search was made with the keywords "Education 4.0 related" to determine those studies that are not explicitly named as Education 4.0 but are relevant content-wise. In this section, the analysis of the studies in Table A.1 and Table A.2 obtained as a result of the searches will be presented based on the column headings in these tables.

In the following analysis section, the search with the keyword “Education 4.0” is called Search 1, and the search with the keyword “Education 4.0 related” is called Search 2.

2.6.1. Analysis of Literature Review

The concept of Education 4.0 first appeared in the literature in 2017. The numbers of the studies obtained when searching with the keyword “Education 4.0” (Search 1) and the keyword “Education 4.0 related” (Search 2) are shown in Table 2.7.

Table 2.7: Year publications and number of studies

Year	Number of studies (Search 1)	Number of studies (Search 2)
2017	3	3
2018	14	11
2019	14	11
2020	10	9
2021	7	4
2022	7	6
2023*	6	5

* These numbers belong to the first 8 months of 2023.

Figure 2.4 shows the article type of studies obtained from searches made according to different keywords. Research papers come to the fore in both searches. While there are 6 review papers in Search 1, there are only 4 review papers in Search 2.

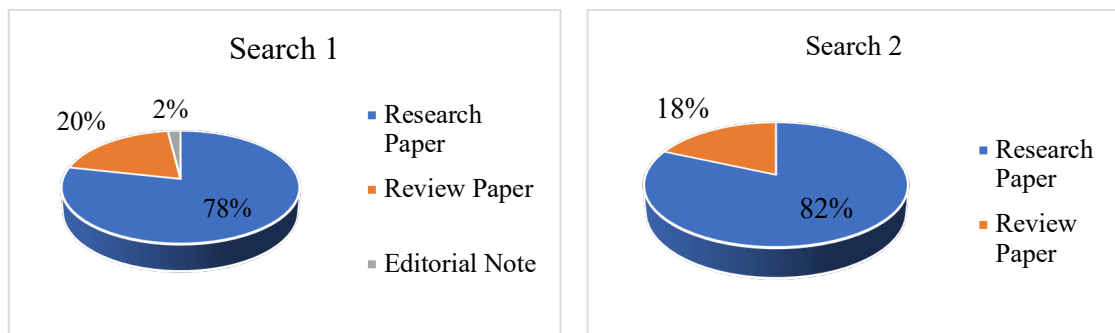


Figure 2.4: Article type

These studies are categorized according to the “aim of the study”. Review papers are divided into three categories as follows:

- *Proposition of conceptual model:* Studies in this category propose a new conceptual model in the field of Education 4.0. Silva and Nadais (2019) present biocentric education model theories previously addressed, until the presentation of paradigm 4.0 for education projected for the future of educators, teachers, and students. Koul and Nayar (2020) propose a holistic learning educational ecosystem conceptual model and explain its elements.
- *Proposition of framework/roadmap:* Studies in this category do not propose a model but rather a framework or roadmap for the subject after reviewing the literature on the subject. Jedaman et al. (2019) propose a roadmap for sustainable education 4.0 in the 21st-century science classroom. The framework that affects the level of motivation toward the integration and implication of Industrial Revolution 4.0 in the education system of Pakistan by considering government policies is proposed by Butt et al. (2020). Viberg et al. (2020) propose a framework for high school mathematics classes where teachers attempted to improve their teaching and student learning by using a digital tool.
- *Presentation of Education 4.0 subject or sub-subject:* Studies in this category are papers that explain Education 4.0 and Education 4.0-related subjects. Waghid (2019) presents the need for Education 4.0 for South African higher education institutions. Xiao (2019) investigates how the importance of digitalization is framed in the strategic growth plans of 75 of China's best institutions. The sustainable management of digital transformation in higher education is presented by Abad-Segura et al. (2020).

Research papers are divided into four categories as follows:

- *Exposure of the essence of Education 4.0:* Studies in this category are papers that reveal the importance of the Education 4.0 concept. Martin et al. (2018) summarize the emerging trends in education concerning the requirements of Industry 4.0 and present possibilities for their use. The main technologies of

Education 4.0, which play an important role in sustaining Industry 4.0 and have a significant impact on reshaping engineering education itself, are presented by Mogoş and Bodea (2019). Buzov (2020) reveals the importance of Education 4.0 for preschool education.

- *Exploration of the readiness of Education 4.0:* Studies in this category are papers that examine the past and future of the Education 4.0 concept and examine whether it is ready in the current educational environment. Terkowski et al. (2019) examine the readiness and availability of online engineering education for manufacturing technology. Jamaludin et al. (2020) investigate the perception, preparedness, and change involved in the implementation of Education 4.0 across the ASEAN area among policymakers, lecturers, and students within the context of globalization.
- *Development of new areas for Education 4.0:* Studies in this category are papers that develop new areas and make applications in those areas so that the Education 4.0 concept can be better integrated into the existing system. Aristin et al. (2020) create unique learning material in the form of aerial imagery-based 3D dry terrain maps using Sugiyono's creation process. Cárdenas and Inga (2020) have devised a methodological plan for students with visual impairment that is centered on the use of meaningful learning with developing technology as the primary guide. The impact of digital transformation on the higher education institutions' business model is explored by Rof et al. (2020).
- *Presentation of a case study for Education 4.0:* Studies in this category are papers that apply case studies related to Education 4.0 and examine these cases. Mohd Adnan et al. (2019) investigate the problems of a tiny number of English educators at Malaysian public institutions who are desperately attempting to use Education 4.0 learning tools to teach this worldwide language to Malaysian students. Torres-Ruiz and Moreno-Ibarra (2019) present the challenges and opportunities in the digital transformation of higher education in Mexico. The demand for digital learning platforms and tools according to the needs of students is investigated by Bujang et al. (2020). The survey was carried out with 320 randomly selected students from diverse disciplines of study at several polytechnics.

In Search 1, the studies included were implemented in various countries such as Malaysia, Pakistan, Indonesia, Germany, South Africa, Mexico, Thailand, and Turkey. As regards their distribution, six studies were from Malaysia, three from Thailand, two from Pakistan and Mexico, and one from each remaining country.

Search 2 contains studies from Australia, Bosnia and Herzegovina, Chile, China, Germany, Greece, Italy, New Zealand, Norway, Mexico, Oslo, Romania, Sweden, South Africa, the Republic of Cyprus, the USA, UK, Ukraine, and Vietnam.

In this study, education levels are divided into categories such as General Education System, Higher Education, Preschool Education, Secondary Education, and Primary School. In both Search 1 and Search 2, the category with the largest number of studies is "Higher Education" (Figure 2.5). There are also many studies conducted in the "General Education System" category, which includes studies on all educational levels without any discrimination.

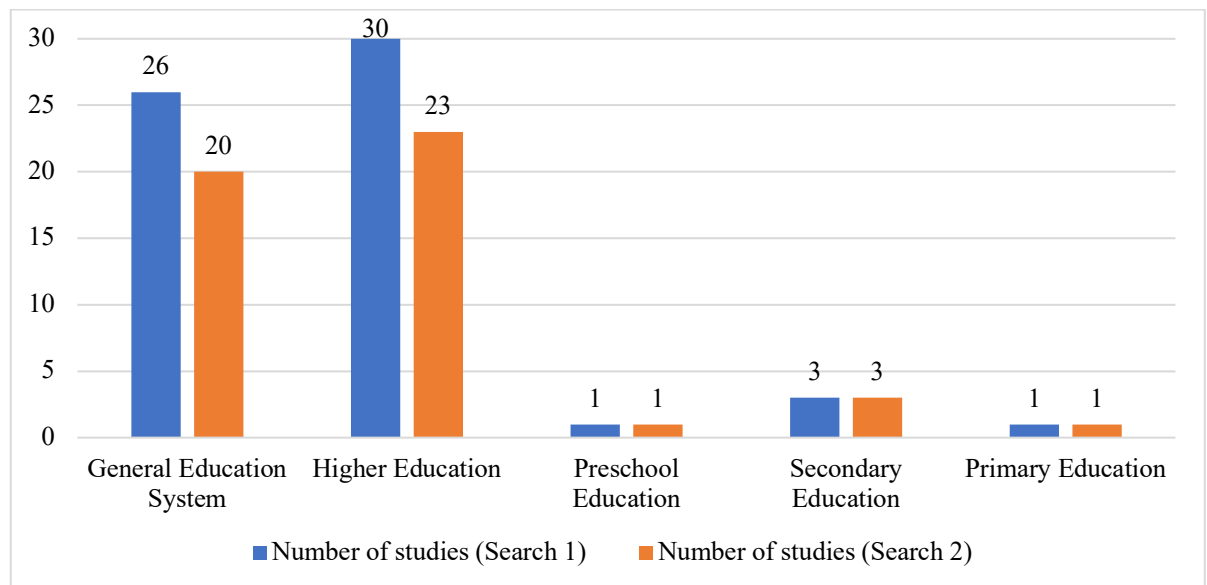


Figure 2.5: Education level

Some of the studies in the literature are applied in a specific educational area. The field with the highest number of studies in Search 1 is engineering education. Ciolacu et al.

(2017) present the Education 4.0 concept in engineering education with artificial intelligence algorithms. Ramirez-Mendoza et al. (2018) describe a new curriculum for Engineering Education 4.0. Mogoş et al. (2018) analyze the main technologies such as robots, 3D virtual worlds, and cloud computing of Education 4.0. Terkowsky et al. (2019) present online education for manufacturing technology in Germany. Polyakova (2020) also presents Education 4.0 for engineering education with fast changes in society including the violent spread of the COVID-19 pandemic.

Other educational areas in this research are language education, industrial education, art education, education for autistic students, and education in the armed forces. Mohd Adnan et al. (2019) examine the struggles of English educators at Malaysian public universities. Cárdenas and Inga (2020) propose a novel methodological strategy based on the usage of language learning with emerging technologies. Mourtzis et al. (2019) present the design and evaluation of a manufacturing system in the concept of industrial education. Nikitakos et al. (2019) present a combination of instructional and communicative learning for shipyard production. Le Van Thang and Dung (2018) present a Higher Education 4.0 model in the armed forces to meet the challenges of Industry 4.0. Shahbodin et al. (2019) support the use of technology in helping autistic learners develop their education/careers. Juan et al. (2019) present an educational tool for social transformation in art education.

The field with the highest number of studies in Search 2 is physical education (Enright et al., 2016; Baert et al., 2017; Bowes & Swanwick, 2018; Walinga et al., 2018; Sargent & Casey, 2018; van Rossum & Morley, 2018; Sargent & Casey, 2019; Calderón et al., 2020). Calderón et al. (2020) examine the relationship between a student-centric approach to new learning and the inherent engagement of pre-service teachers using statistical methods.

Other educational areas in this research are teacher education, entrepreneurship education, mathematics education, and childhood education. Madsen et al. (2018) study the effect of different national strategies for implementing digital technology in Norway and New Zealand. Constantinou and Papadima-Sophocleous (2020) explain the use of

digital technologies for English Specific Purposes. Secundo et al. (2020) present the digital transformation of entrepreneurship education in Italy. Viberg et al. (2020) propose the integration of digital technology in mathematics education. Madanipour and Cohrssen (2020) examine the use of Augmented Reality for education. This technology enables students to understand abstract concepts and visualize events that cannot be easily discovered in real life.

Table 2.8: Used technology and number of studies

Used technology	Number of studies (Search 1)
Internet of Things	6
Virtual Reality	5
Artificial Intelligence	4
Augmented Reality	4
Machine Learning	3
Cloud Computing	3
Big Data	2
Robots	2
Smart Sensors	1
Cyber-Physical Systems	1
3D Mapping	1
Blockchain	1
5G Technology	1

Digital technologies were found to have been used more in Search 1 studies than in Search 2. The used technologies and the number of studies are each shown in Table 2.8. Ciolacu et al. (2017a) evaluate the performance of students with Machine Learning methods. Tanriogen (2018) determines the possible effects of Industry 4.0 on the Turkish Educational System with digital technologies such as the Internet of Things, Autonomous Robots, Augmented Reality, and Big Data. Ciolacu et al. (2018) estimate students' final scores before taking part in an Artificial Intelligence and Machine Learning exam. Miranda et al. (2019) explain how Open Innovation Labs are used as tools for realizing the Education 4.0 vision. Cárdenas and Inga (2020) suggest a new

analytical approach focused on the use of digital technology for practical learning. Haque et al. (2023) proposed a systematic meta-analysis of blockchain technology for the educational sector. 5G-enabled Education 4.0 with technologies, challenges, and solutions is presented by Kizilkaya et al. (2021).

In the studies in Search 2, augmented reality, virtual reality, artificial intelligence, and Internet of things are used. Kushzhanov et al. (2018) present the digital transformation of the education system with virtual reality. Roberts-Yates and Silvera-Tawil (2019) report on their investigations into the role of digital technology in providing educational opportunities via the use of Virtual Reality for students diagnosed with an intellectual disability. Madanipour and Cohrssen (2020) present the use of augmented reality for childhood education.

When looking at the Education 4.0 literature, it is striking that the number of studies in which analytical methods are used is low. Some of the main analytic methods that are used are statistical methods, association rule mining, simulation, three-layer architecture, neural networks, and cluster analysis. Hartono et al. (2018) produce a model of the smart hybrid learning method by using three-layer architecture. Mogoş and Bodea (2019) present recommender systems for Education 4.0 with association rule mining. Lazar et al. (2020) develop, validate, and test an extended Technology Acceptance Model with statistical methods.

2.6.2. Analysis of Bibliometric Mapping

VOSviewer is a software tool that allows you to create maps based on network data and then see and explore them. VOSviewer (version 1.6.18) was used to examine and analyze the studies obtained as a result of the literature review.

Firstly, a co-authorship analysis based on "country" is conducted. 49 countries in which the studies were published are identified, and only 28 of these countries are linked to each other. The map in Figure 2.6 shows that Mexico is the country with the most

cooperation in co-authorship studies in the field of Education 4.0, followed by Malaysia, India, and Spain, respectively.

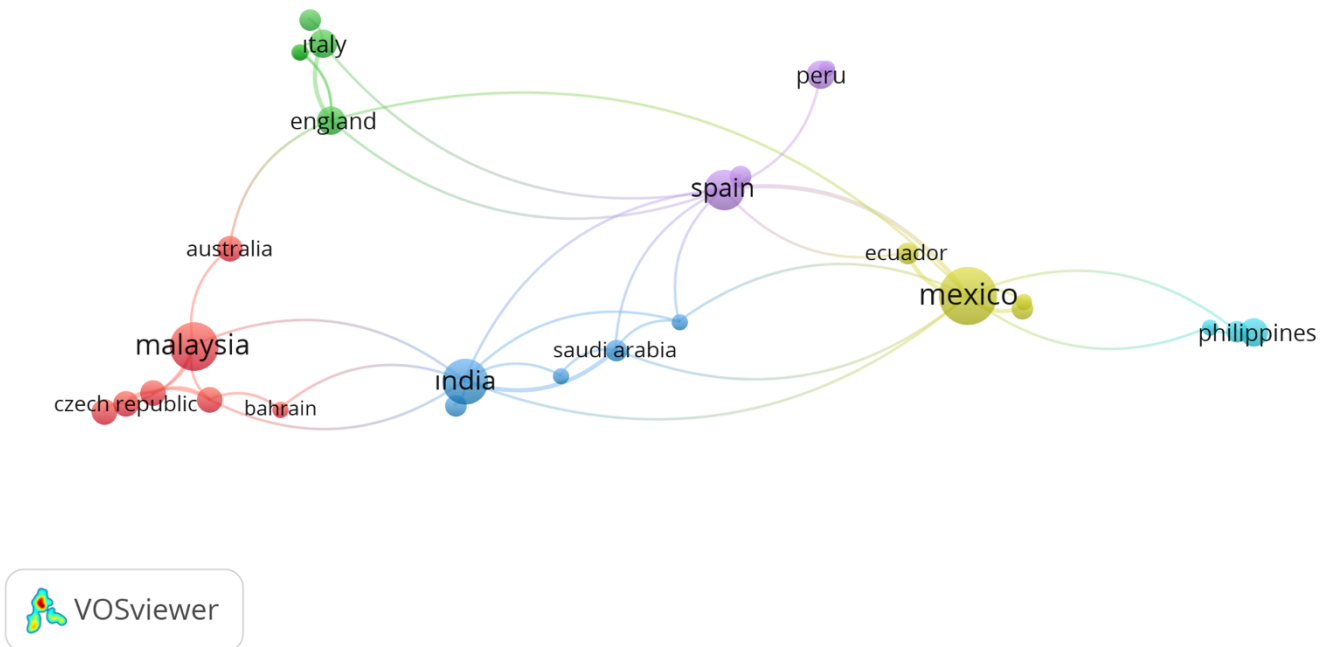


Figure 2.6: Co-authorship network based on country

Another analysis carried out within the scope of the research is the citation network map, whose analysis unit is the document. A citation link connects two things in which one cites the other. VOSviewer treats citation links as undirected. As a result, there is no differentiation between a citation from item A to item B and a citation in the other way. The analysis was applied by including the studies with at least 1 citation out of 128 documents, 82 studies satisfying the condition were selected and a cluster containing 33 interrelated items was reached. It is common practice to set a lower limit to obtain more refined outputs in this type of research with intensive data. The visual of the documents presented with the citation network map is presented in Figure 2.7.

Accordingly, the studies with the highest citation network connection can be listed as Mourtzis et al. (2018), Grodotzki et al. (2018), and Bonfield et al. (2020). It is not surprising that Mourtzis et al. (2018) achieved this result with their work in Industry 4.0 and Education 4.0. Their work, in which they presented the use of cyber-physical systems, especially for Education 4.0, are widely cited in the literature.

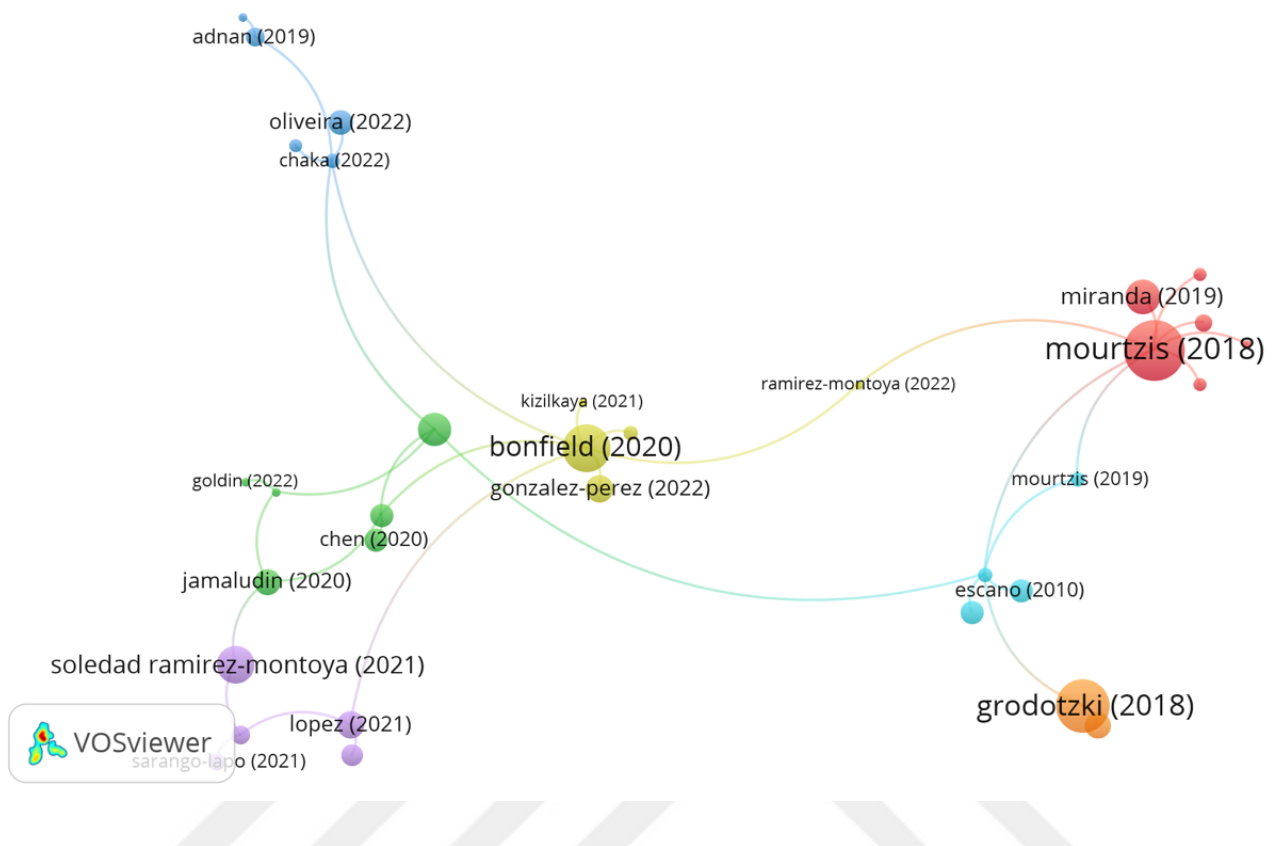


Figure 2.7: Citation-based network based on document

Journals have a special place in scientific communication. Determining the journals that are frequently referenced in a field allows field researchers to identify the leading journals in the field and structure their studies according to journal policies. In the study, journal (source) co-citation analysis is carried out to identify the journals that are co-cited in the bibliography of the articles related to Education 4.0 listed in WoS. This analysis is shown as density visualization as in Figure 2.8.

The network map was created with 76 journals cited at least 6 times out of a total of 2659 journal citations. Six clusters stand out in the density map in Figure 2.8 of the most frequently cited journals in articles on writing skills listed in WoS. The red cluster has 22 nodes, the green cluster has 15, the blue has cluster 10, the yellow cluster has 8, the purple cluster has 8 and the orange cluster has 7 nodes. The densest cluster is red, and the loosest cluster is orange. Accordingly, Sustainability, Computer & Education,

IEEE Access, and Computers in Human Behavior are among the sources with the highest bibliographic matching network power.

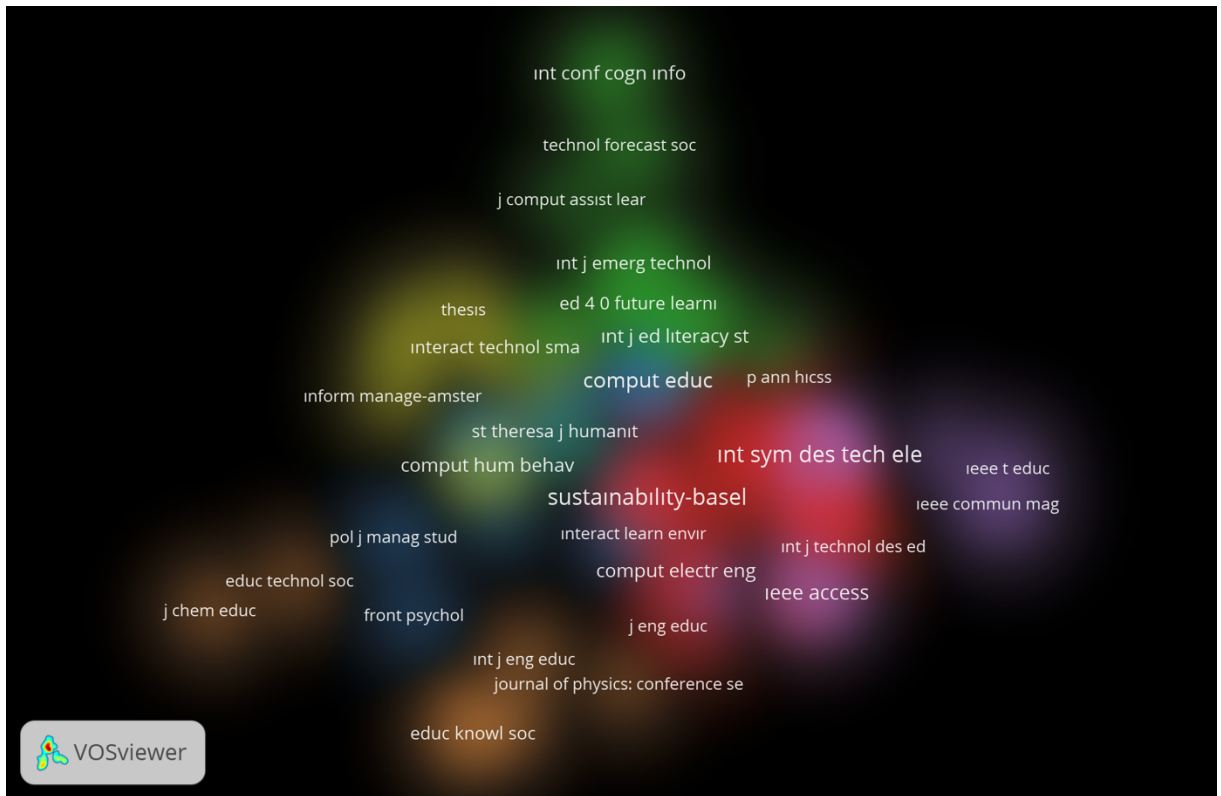


Figure 2.8: Co-citation density visualization based on source

The keywords used by the author in scientific research are decisive in terms of understanding the structure and content of the study. When describing these scientific articles, researchers create keywords that summarize their work. In this context, the presence of two close keywords in the same article indicates a relationship between the topics it covers. The relevant literature can be evaluated thematically by determining those points at which the keywords assigned to the studies by the authors are concentrated. In this analysis, co-occurrence analysis was performed based on author keywords to understand the scientific orientation of the articles related to Education 4.0 listed in WoS. This analysis is shown in Figure 2.9 as an overlay visualization.

The core keywords in the articles examined and the density of the most frequently seen terms are determined systematically. The conceptual structure of 62 word-pairs meeting

the threshold value of “2” out of 410 keywords assigned to the Education 4.0 related articles is mapped in Figure 2.9.

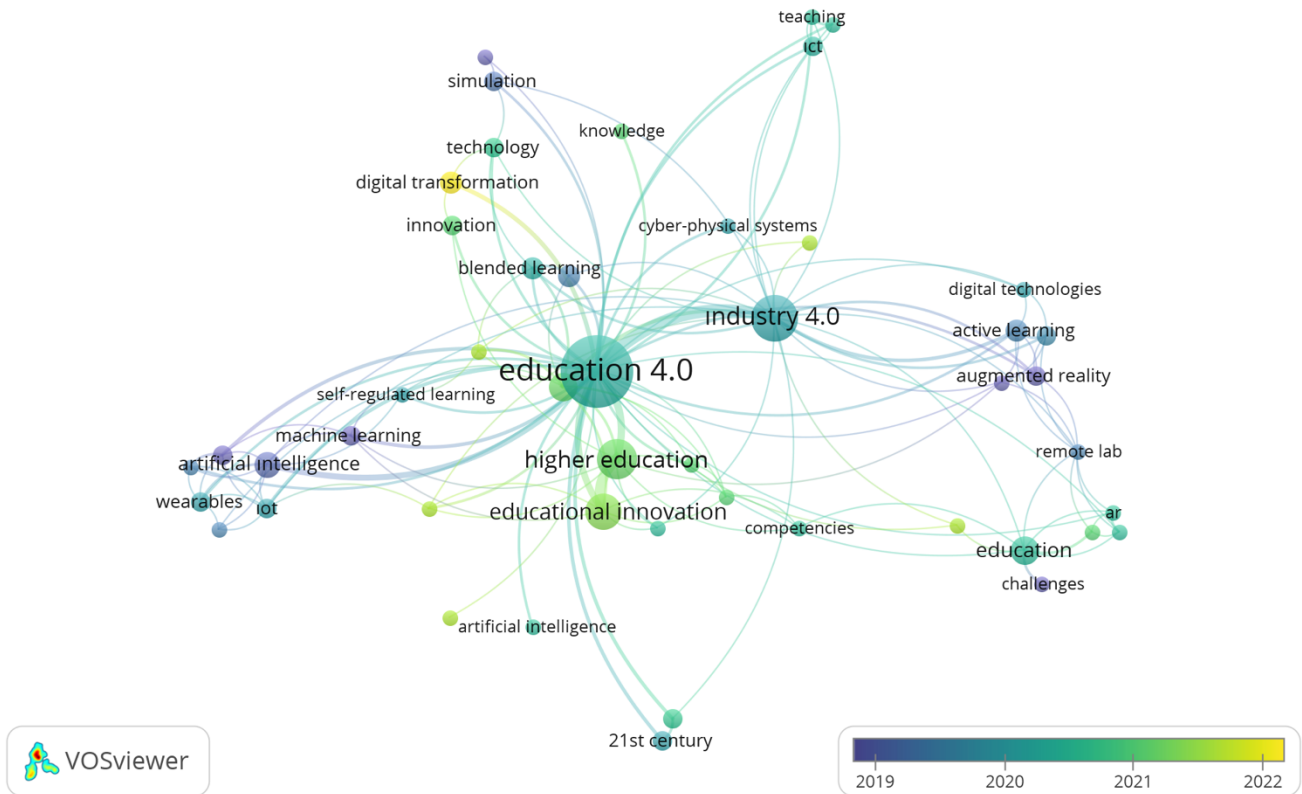


Figure 2.9: Co-occurrence overlay visualization based on author keywords

As seen in Figure 2.9, the most prominent keywords in the literature are "education 4.0" and "industry 4.0". Both of their use increased in late 2019 and early 2020. The COVID-19 pandemic may be effective in this situation. Considering the distribution of keywords by year, digital technologies such as "augmented reality", "machine learning", and "artificial Intelligence" are used in 2019. In 2020, the concepts of "cyber-physical systems", "wearables", and "blended learning" are at the forefront. In 2021, it is seen that the keywords "educational innovation", "higher education", "skills", and "competencies" are frequently used. By 2022, the concepts of "digital transformation", "industrial revolution 4.0", "learning factories", and "cloud computing" come to the fore.

Secondly, co-occurrence networks are created by examining the text data with natural language processing. Natural language processing techniques are used to identify terms in text data. The word identification stage's natural language processing algorithms presume that the text material that was made accessible to VOSviewer is in English. With this tool, the abstract sections of studies are examined and the related keywords are mapped as in Figure 2.10.

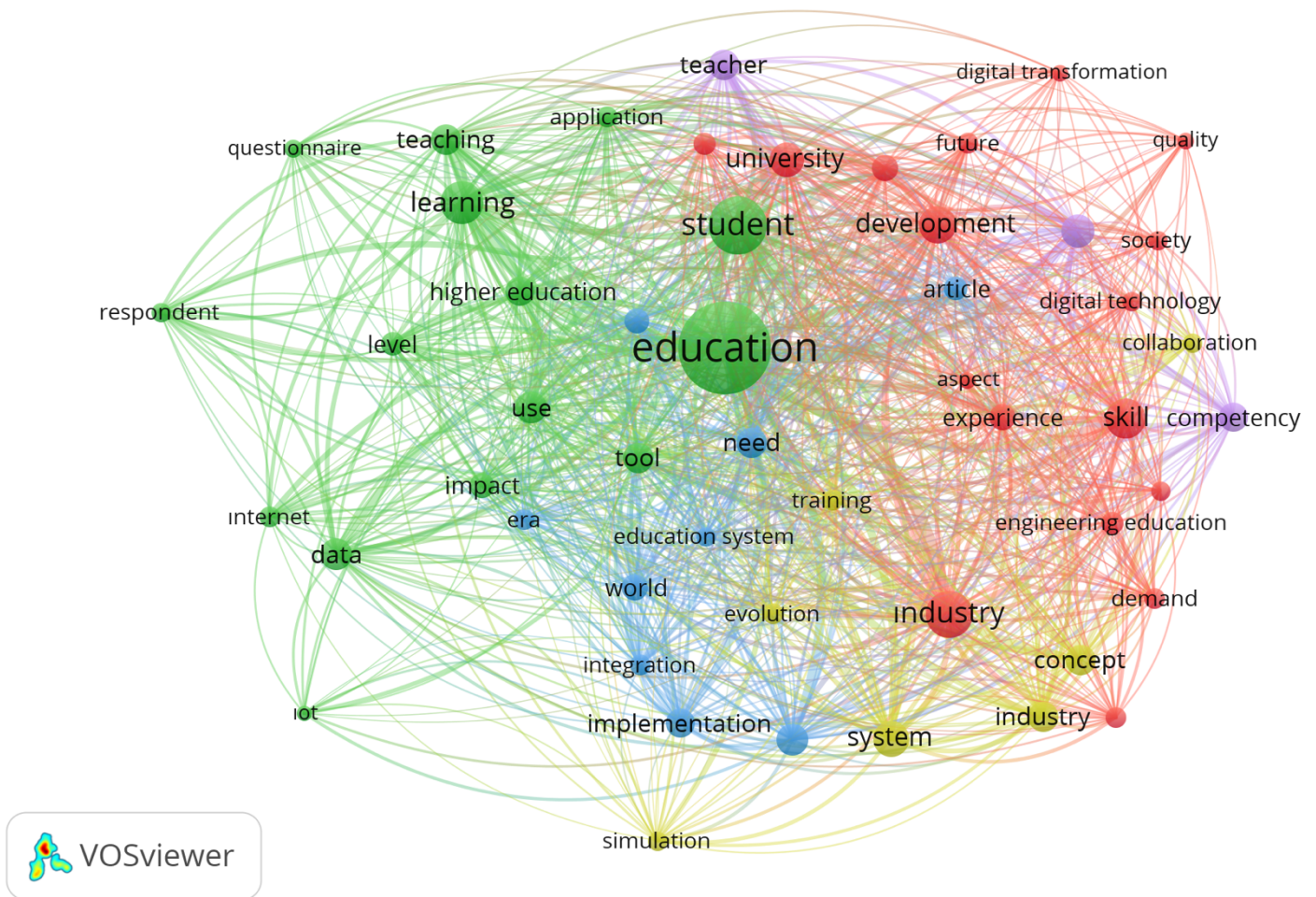


Figure 2.10: Co-occurrence network with the text data

As seen in the figure, there are five separate clusters: green, red, blue, yellow, and purple. The green cluster constitutes a large part of the studies and focuses on the concepts of education, students, learning, and teaching. In the red cluster, which is one of the other densest clusters, concepts such as industry, development, university, and digital technologies come to the fore.

While the network created in Figure 2.9 is based on the keywords determined by the authors in the studies, this network in Figure 2.10 was created by analyzing the abstract sections of these studies.

According to the review results, it is seen that the concepts of digital technologies, Education 4.0, and digital transformation are intertwined related concepts. As a result of the literature review conducted in this context, it is possible to say that digital technologies have changed over the years. Table 2.9 shows in which years digital technologies were used.

Table 2.9: Year-wise classification of published literature in digital technologies in education and Education 4.0

Year	Digital technologies with references
2017	AI (Ciolacu et al.), ML (Ciolacu et al.)
2018	AI (Ciolacu et al.), AR (Martin et al., Benešová et al., Tanriogen), BD (Maseleno et al., Tanriogen), CC (Mogoş et al.), CPS (Mourtzis et al.), IoT (Ciolacu et al., Tanriogen), ML (Ciolacu et al.), Rob (Mogoş et al., Tanriogen), VR (Kushzhanov et al.; Mogoş et al.)
2019	AR (Miranda et al.), CC (Kloos et al.), IoT (Miranda et al.), ML (Kloos et al.), VR (Mohd Adnan et al., Juan et al., Miranda et al., Roberts-Yates & Silvera-Tawil)
2020	3D (Aristin et al.), AI (Butt et al.), AR (Madanipour & Cohrsen), IoT (Butt et al., Cárdenas & Inga)
2021	5G (Kizilkaya et al.), AI (Kizilkaya et al.), IoT (Gutiérrez-Martínez et al.)
2022	CC (Verma et al.), IoT (Verma et al.)
2023	BC (Asad & Hussain), VR (Asad & Hussain)

3D Technology (3D), 5G Technology (5G), Artificial Intelligence (AI), Augmented Reality (AR), Blockchain (BC), Big Data (BD), Cloud Computing (CC), Cyber-Physical Systems (CPS), Internet of Things (IoT), Machine Learning (ML), Robotics (Rob), Virtual Reality (VR)

It is seen that the technologies used in the field of digital education are in the majority in 2018. This situation shows parallelism with the changing industry approaches and

business practices with Industry 4.0. At the same time, 2018 was the year when the use of AR technology worldwide increased. In 2019, the use of technology continues to develop and the use of VR technology is increasing (Williamson et al., 2020). In 2020, it is seen that the focus is on certain technologies. You can see the details of these studies in Table A.1 and Table A.2. In addition, the distribution of digital technologies by years is shown in Figure 2.11.

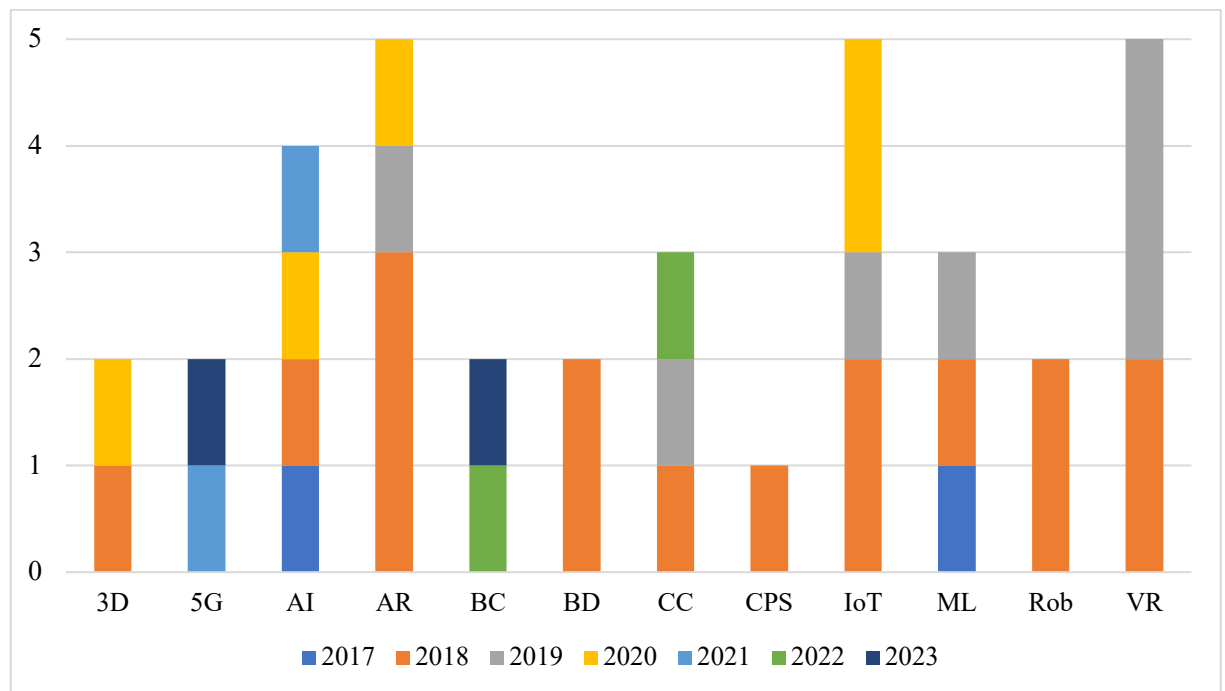


Figure 2.11: Digital technologies based on years

2.7. Findings

RQ1: What are the characteristics of the Education 4.0 concept as supported by digital technologies in the provision of a quality and sufficient education environment?

Looking at the literature, there are many different features and methods regarding the concept of Education 4.0. However, no study brings together the most representative features of Education 4.0. The main characteristics of Education 4.0 determined as a result of the literature review are as follows:

- *Time and place independent education:* With Education 4.0, students can study wherever and whenever they want. Education is evolving into a modern medium independent of location and time, thanks to new interactive learning technologies. Thus, while the analytical component is learned outside the classroom, face-to-face practical learning is done in the classroom. Moreover, the student can conduct their education with e-learning resources in their own space, with the benefit of time independence (Pooworawan, 2015).
- *Personalized learning:* Students benefit from personalized learning opportunities through special tools, where difficulty levels are adjusted according to their capacities. In this way, students who have difficulty understanding something that other students may grasp more easily can make up for their deficiencies through personal effort in their own time. Intermediary software does not raise the level of difficulty until the student reaches the desired level. With this advantage of personalized learning, students who experience a loss of self-confidence by thinking that they are academically insufficient are provided with an opportunity to close their gap. When the performance graphics obtained from software are examined by the teachers, it is possible to have an idea about the student's field susceptibility (Hooshyar et al., 2020). Teachers can easily and effectively identify which student needs help and in which area they should be directed. The contents of the education can be enriched according to the learning speed and status of the students. Instead of adapting the students to the education system, it will be possible to shape the system according to the student's abilities (Van Popta et al., 2017).
- *Learning flexibility:* Traditional education systems apply their education model with the same method for each student. Education 4.0 provides a flexible education model for every student. Educators give specific directions to advance the aspects of the student according to their skills, such that students can improve on their weaknesses thanks to an adaptive education plan. For instance, a successful student in mathematics can complement their weak verbal development with a stretched learning plan (Van Popta et al., 2017; Ciolacu et al., 2018). Although the purpose of the lessons is to take the student to a certain point, the path that each student will follow to reach the targeted point may be

different. Students will be able to design their own learning processes with tools that are suitable for them with personalized learning tools. They will be able to perform flexible learning with their education programs and tools freely shaped in line with their preferences. Learning with new approaches such as blended learning, classless learning, and learning with their own devices will be important (Hooshyar et al., 2020).

- *Project-based learning/Application-based learning:* To prepare children for the flexible working model of the future, students adapt to project-based learning and working models. They apply what they have learned to a real project instead of writing on paper. In other words, instead of abstract knowledge, practical skills come to the fore in the learning process. Organizational skills to be used in business life, teamwork, and time management skills are ingrained in students while they are at school (Van Popta et al., 2017; Núñez-Canal et al., 2022). For this purpose, environments are created where students can use their skills. Complementary opportunities such as internships, simulations, and mentoring programs are offered.
- *Data interpretation:* Computers are increasingly capable of making all kinds of statistical analyses, analyzing data, and making predictions. Interpretation of the results, however, still is the role and responsibility of educators and students. The most important indicator of being literate will now be the ability to apply theoretical knowledge to numerical data (data analysis) and identify trends and patterns from these data. Students will largely benefit from advanced data analysis and interpretation skills, such as the establishment, management, development, collection, and processing of data systems. As one of the important requirements of Education 4.0, students should be able to recognize the data, formulate analyses, and comment on it. Thus, students can learn to approach standard data from a novel perspective (Hooshyar et al., 2020; Lynch et al., 2021).
- *Assessment approach not examination:* In the current system, students are evaluated with an exam based on questions and answers. Lacking any relationship to direct experience, much of the memorized information is generally forgotten after the exam. In Education 4.0, instead of examination, the

application is made the focus of evaluation. It is aimed to use the information acquired by students as soon as they start their professional life. In this context, the student's knowledge is based on the evaluation of the entire education period instead of a single exam (Miranda et al., 2019; Milićević et al., 2021). Throughout the learning process, their knowledge will be continuously measured and tested in terms of the performance of the projects they are working on. Students who learn coding, for instance, develop a calculator or game that they can use in their daily life, instead of just knowing the theoretical information. These projects contribute to the transformation of theoretical knowledge into practical experience and storage in long-term memory (Ciolacu et al., 2017b).

University curricula target a complete set of competencies for the European Higher Education Area entailing not just theoretical knowledge but also skills, talents, and attitudes relevant to the subject of knowledge and, most importantly, professional reality. Competency-based assessment can be facilitated by the incorporation of information and communications technology in the learning-teaching-evaluation system, resulting in the establishment of new educational possibilities and more flexible and individualized knowledge (Ion et al., 2016; O'Donovan et al., 2022). Metacognitive self-regulation is an essential component of learning, and student competency development includes reflection on and self-regulation of activities occurring within teaching-learning situations (Allal, 2000).

- *Curriculum with student participation:* Students play a more active role in creating their own curriculum. Creating a contemporary, up-to-date, and useful curriculum is possible with the participation of students as well as professionals. Considering students' views on the curriculum is one of the indispensable parts of a more inclusive education program. With the inputs given by the trainees, the importance and necessity of different issues can be discussed. Curricula consisting of information stacks are replaced by curricula that are based on up-to-date information and needs that are collaboratively identified (Saribas & Çetinkaya, 2021).

- *Guidance-based:* In a world where the volume of data is growing wildly and information is rapidly multiplied and diversified, the student can understandably need some form of counseling and guidance. A qualified mentoring system is a valuable element in this respect. The learning processes of the students will be more independent, guided by a mentor as a critical element for contributing to the student's success. Since education will be carried out remotely, teachers and educational institutions will be more important for academic performance. Virtual mentors will be actively used in the world of Education 4.0 (Ishak & Mansor, 2020).

RQ2: Is it possible to create modules suitable for all users in an Education 4.0 framework and how much are users expected to benefit from this approach?

To get the maximum benefit from Education 4.0, the education system should be transformed into a more personalized form. One of the most important features of the new education model is that it is personalized, wherein students use study tools tailored to their abilities. In this setup, students above the average will encounter more difficult tasks and questions after exceeding a certain learning bar. In this concept, education will develop depending on each individual's ability and pace.

Predicting the progress of education based on each person's own ability means that the individual will have the opportunity to return if they experience problems in learning. Students can repeat the topics until they have reached the desired level. The aim is to ensure students who face difficult learning conditions do not experience educational barriers due to low morale, loss of motivation, or lack of confidence. At the same time (with the support of artificial intelligence applications) tutors will be able to understand students' progress levels (Wallner & Wagner, 2016; Ciolacu, 2018).

Such personalization implies that students' progress to different goals through different learning paths according to their needs. They can try different tools, techniques, software, and applications. Information technology will assist in, for example, making statistical analyses and predicting future trends. Interpretation, evaluation, and

transformation of the obtained results, i.e. application of such information through human reasoning and analysis skills, will certainly be a critical factor in the future of education (Puncreobutr, 2016; Nikitakos et al., 2019).

In this context, the steps that can be taken to integrate personalized education into the existing education system can be listed as follows (Ion et al., 2016; Hussin, 2018; OECD Report, 2019; Hooshyar et al., 2020; O'Donovan et al., 2022):

- *Profiling students:* It includes guiding students to set learning goals, using data such as test results, projects, and students' desires and attitudes.
- *Creating personal learning paths:* It aims to provide flexibility in the student's choice of subjects to learn by using a variety of teaching approaches and providing personal support.
- *Competence-based progression:* It emphasizes the importance of allowing the student to work on topics suitable for their level and giving them the necessary time to fully learn the topic they are working on before moving on to another topic.
- *Creating flexible learning environments:* It is to arrange the time, staff, and physical environment to meet the student's needs.

Personalized education increases success for students regardless of their initial level of achievement. Analyses show that the effects of institutions may be more positive after gaining experience in implementing personalized education.

RQ3: Which digital technologies are used in Education 4.0 applications and which of these technologies is the most efficient for users?

Looking at the literature, there are many digital technologies integrated with Education 4.0. However, there is no study on which of these technologies facilitates the most appropriate strategy.

New technologies are developing all the time, which will also be a part of education systems. With digital technologies, access to all courses and courses on the internet will be possible. Web interfaces and access systems will be implemented for students to learn most appropriately. Education 4.0 will use these technologies both in the creation of education systems and tools and will make it a part of the education program for students to learn (Kloos et al., 2019; Juan et al., 2019; Cárdenas & Inga, 2020). According to the results of this literature review, the main technologies integrated with Education 4.0 are as follows:

- *Internet of Things*: Network of physical objects that communicate with each other and can support physical/virtual integration. This technology refers to the connected tools in the Internet of Things, a world where data is collected and devices interact with each other and human-robot interaction is possible. With the interconnection of devices in networks, IoT applications in education have become possible by embedding sensors in library resources, board surfaces, game boards, and robots, which are physical areas on campus. Student profiles can be mapped to physical campus spaces such as “classrooms, labs, libraries, and gyms,” and wearable devices can enable students to access desired content conveniently (Tanriogen, 2018; Miranda et al., 2019; Kassab et al., 2020).
- *Artificial Intelligence*: Artificial intelligence is the use of high-level cognitive skills by a computer to display human-like behaviors such as reasoning, problem-solving, inferring, and generalizing. Intelligent Instructional Systems, which can be considered the second generation of computer-assisted teaching as one of the artificial intelligence processes, are among the most used applications of artificial intelligence in education. In general, Intelligent Educational Systems provide personalized learning environments that are appropriate and step-by-step for each student through well-structured subjects such as medicine, mathematics, or physics (Ciolacu et al., 2018; Holmes et al., 2020).
- *Virtual Reality*: Virtual reality simulates a virtual world through equipment and uses computers to generate a simulated education environment, which emphasizes real-time interaction of users with the virtual world and creates a

closed-loop, immersive virtual world experience (Kushzhanov et al., 2018; Juan et al., 2019; Roberts-Yates & Silvera-Tawil, 2019).

- *Augmented Reality*: Augmented reality uses computer graphics technology and visualization to produce virtual objects that do not exist in the real world, and accurately "place" the virtual objects in the real education world, putting users in an intertwined real-virtual education world (Martin et al., 2018; Tanriogen, 2018; Juan et al., 2019; Madanipour & Cohrsen, 2020).
- *Cloud Computing*: Cloud computing is a technology that provides on-demand network access to the sharing pool of computer resources that can be arranged such as network, server, storage, applications, and services (Mell & Grance, 2011). Cloud-based education applications transfer the infrastructure installation, maintenance, and management processes, which are a burden on educational institutions, to the control of cloud service providers. This enables educational institutions to focus on the quality of their education (Li & Chen, 2011).
- *Machine Learning*: Machine learning is an evolving branch of computational algorithms designed to mimic human intelligence and model a problem with a data-appropriate algorithm (El Naga & Murphy, 2015). With the machine learning methods used in the field of education, it has become possible to do educational data mining, develop intelligent teaching systems, produce automatic recommendations for teachers and students by the system, and develop adaptable and individualized educational environments (Ciolacu et al., 2017a; Ciolacu et al., 2018; Bargagna et al., 2019).
- *Robotics*: With the use of robotics in education, students' problem-solving skills develop and their success, attitudes, and interests toward STEM fields change. In addition, using social robots in the learning process of students with Down syndrome who need special education, makes it easier to adapt them to science and mathematics education. Thanks to its programmable feature, educational robots allow students to see their operations instantly (Ciolacu et al., 2018; Calderón et al., 2020).
- *Big Data*: Big data are high-volume, high-speed, and/or high-variety information assets that demand cost-effective, innovative forms of information

processing that enable enhanced insight, decision-making, and process automation (Gartner IT Glossary, 2012). In a big data indexed approach, mass data is reached by collecting individual data. By analyzing the data collected individually, their future performance and behavior are predicted and planning is made accordingly. In this way, the efficiency of the materials used individually can be evaluated and success can be achieved by using big data in individualized learning (Tanriogen, 2018).

- *Smart Sensors:* Smart sensors give a more sophisticated set of protections by building on existing sensor and detection technology. Smart sensors have a much wider range of inputs than traditional sensors, which can only detect simple environmental changes like temperature increases, the movement of physical items, or the presence of smoke. They serve a wider range of purposes, which makes them crucial for administration teams in educational institutions because they safeguard everyone's health, safety, and overall well-being while they are on the property (Cárdenas & Inga, 2020).
- *Cyber-Physical Systems:* Cyber-physical systems consist of a combination of smart physical components, objects, and systems with embedded processing and storage facilities. They are connected globally via internet networks. Cyber-physical systems essentially enable the creation of educational environments with the ability to communicate and network between systems and individuals. It offers new possibilities in the field of distance education. Intelligent control systems can easily communicate with each other with embedded software and physical system networks. An intelligent laboratory built through cyber-physical systems increases the quality of education (Mourtzis et al., 2018; Calderón et al., 2020).
- *3D Virtual Worlds:* 3D virtual worlds are network-based desktop virtual reality environments in which users move and interact in 3D simulated environments. These virtual worlds support the constructivist learning approach with the opportunity to learn by living, can reduce educational costs thanks to their 3D opportunities, can be used as a useful tool in distance education with its accessibility and sense of presence, facilitate learning, provide learners with a

unique experience, and contribute to foreign language learning (Dickey, 2005; Martin et al., 2018; Girvan & Savage, 2019; Miranda et al., 2019).

- *3D Mapping*: 3D mapping technology employs machine vision to help in the profile of three-dimensional objects to map them in the real world, giving the most advanced technological approaches for visualization and information collecting. 3D mapping is used in applications for child education in geography lessons. The most important element in the readability of a map and its interaction with the user is the graphic language. Children's map reading and comprehension capacities increase with 3D maps. In the case of 3D maps, it was necessary to predefine optical 3D symbolization variables. The concept of virtual reality and the simulation of the real world it provides support 3D mapping (Papadopoulos et al., 2003; Ciolacu et al., 2018).

In this context, it is necessary to evaluate these technologies and determine the most appropriate for Education 4.0. With these adaptive learning technologies, the learning platform is shaped according to individual student data and educational resources change accordingly using cloud computing and learning analytics. With Big Data, curricula can be designed using data collected from students. The Internet of Things can connect people, things, and devices. Students carrying smart devices can benefit from the information transferred to them from their environment. Wearable technologies can integrate exercise diaries, location information, and visual reality tools into the learning environment (Martin et al., 2018; Miranda et al., 2019).

In the Education 4.0 vision, the learning process is increasingly more related to the learner and his/her needs, taking into account also the personalization of the learning process. The learner must take decisions regarding his education. These technologies offer answers and alternatives to most of the aforementioned questions, such as delivery methods for educational content, teaching approach, collaborative work, knowledge enhancement, industry requirements, and job-specific knowledge (Mogoş et al., 2018).

Many education systems focus on technical areas, such as big data, digital glasses, wearable technologies, the Internet of Things, smart cities, unmanned autonomous

factories, and 3D printers. Other skills will be needed in the future as well, such as analytical thinking, affinity with digital culture, intellectual capital management, idea banks, producing project and scenario-based solutions to sociocultural events, being proactive, focusing on the big picture, and similar. Societies need to reorganize their education systems by determining a roadmap where they can experience the inevitable digital transformation in the most appropriate way for them (Puncreobutr, 2016; Ciolacu et al., 2018; Calderón et al., 2020).



3. METHODOLOGICAL BACKGROUND FOR USED APPROACHES

This chapter includes the proposed evaluation approaches used throughout the thesis such as MCDM-based, QFD-based, and index-based evaluation, the details of these approaches, used fermatean fuzzy technique, used fermatean fuzzy MCDM methods, and the computational steps of the proposed evaluation approaches in this thesis.

3.1. Proposed Evaluation Approaches

3.1.1. MCDM-based Evaluation Approach

Realistic decision-making situations are frequently too complicated and insufficiently organized to yield the best outcome. In reality, a one-dimensional approach oversimplifies the true nature of the problem and might lead to unrealistic conclusions. MCDM is a branch of operations research that focuses on the creation and use of decision-making tools and procedures for dealing with complicated choice situations. When you have many, typically opposing criteria, MCDM helps you to make a choice. It is one of the most often used approaches by researchers in the literature (Hwang & Yoon, 1981).

In MCDM, there are two branches. There are two types of decision-making: multi-attribute decision-making (MADM) and multi-objective decision-making (MODM). MADM typically incorporates discrete decision variables and a restricted number of assessment options (Jato-Espino et al., 2014). MODM is concerned with selecting the optimal alternative from an infinite collection of possibilities while adhering to a set of limitations. In MODM, each criterion is linked to a goal, but in MADM, each criterion is linked to a discrete characteristic (Kabir et al., 2014). However, in recent years, the

terms MADM and MCDM have been used interchangeably to refer to the same class of issues.

MCDM gives the best of all alternatives in the environment of multiple, usually conflicting, decision criteria. Priority-based, distance-based, and mixed methods can be considered the main classes of the current methods (Pomerol & Barba Romero, 2000). Experts are trying to make decisions by combining different information. However, it isn't easy to decide when there are many criteria and sufficient information. Therefore, the fuzzy MCDM approach is used to reveal information in uncertain situations. In this thesis, the MCDM approach is used to evaluate digital education platforms. In addition, MCDM methods are integrated with other approaches.

3.1.2. QFD-based Design and Evaluation Approach

QFD is an important design approach that allows the transfer of customer demands to product or service characteristics in all functional components, as well as a tool for planning, development, and communication (Akao et al., 1990). QFD is a strategic technique for developing better goods and services that are responsive to user wants. This method seeks to transform the URs into the TRs.

In the QFD process, the HoQ shown in Figure 3.1 is the most commonly utilized matrix. A team of interdisciplinary professionals conducts the HoQ matrix to transform URs from market research and benchmark data into TRs that will be addressed by building a new product or service (Hauser & Clausing, 1988). This matrix is intended to analyze the TRs for metaverse-based education by addressing URs. This method has defined URs, and it aims to boost customer satisfaction by addressing user demands. At the same time, design optimization and efficiency will increase. It is a systematic algorithm that is employed as the primary design tool in QFD. It organizes data and develops relationships (Chan & Wu, 2002).

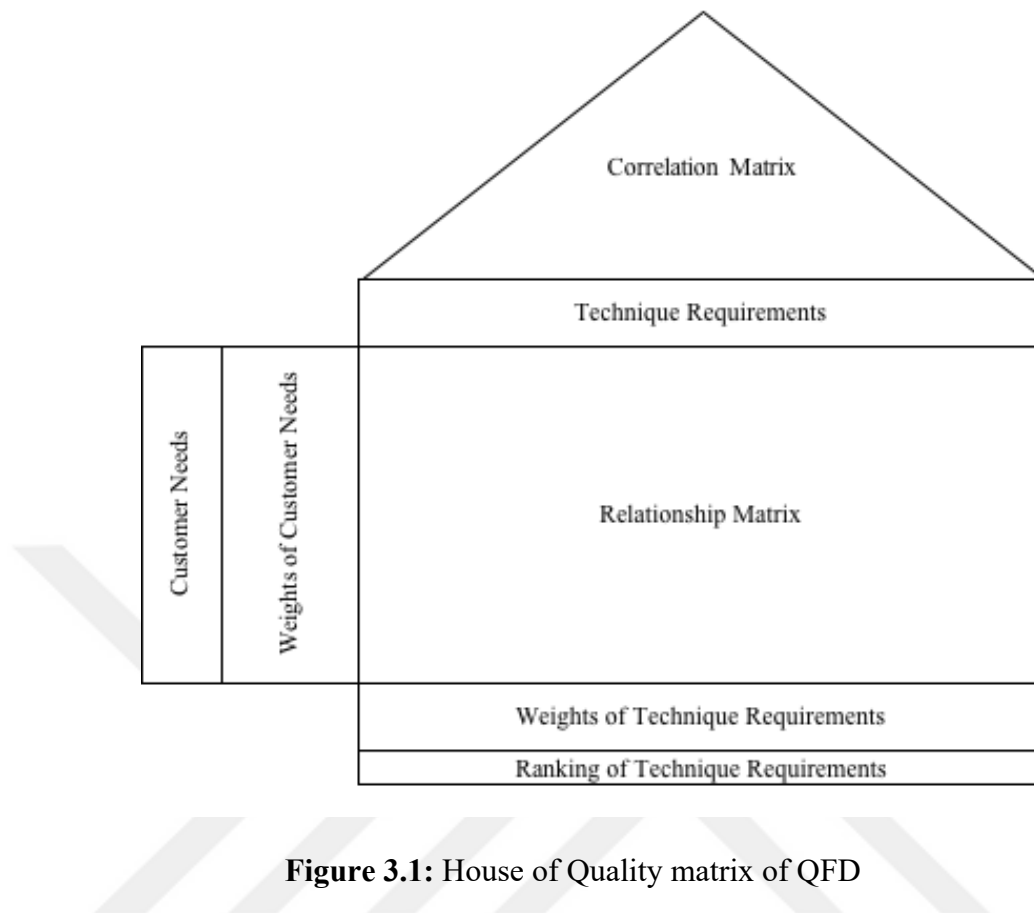


Figure 3.1: House of Quality matrix of QFD

To address the issues of uncertainty and imprecision in QFD, multiple advanced fuzzy QFD approaches have been created by combining advanced fuzzy MCDM with QFD. The fuzzy AHP method is one of the most integrated methods with the QFD approach. The studies in the literature examining the QFD approaches integrated with the advanced fuzzy AHP method are listed in Table 3.1.

In the literature, the QFD methodology has been integrated with the fermatean fuzzy approach (Seker & Aydin, 2023), but no MCDM technique has been used. In this thesis, unlike other studies in Table 3.1, the AHP based QFD methodology is integrated with the fermatean fuzzy approach for the first time. In addition, this method is integrated with aggregation operators in the field of digital technology assessment for metaverse-based education.

Table 3.1: Papers concerning QFD and advanced fuzzy AHP techniques

Year	Author(s)	Advanced fuzzy AHP techniques	Application area
2014	Jenab et al.	Interval valued fuzzy AHP	warranty management
2016	Onar et al.	Hesitant fuzzy AHP	computer workstation selection
2019	Wang	Intuitive fuzzy AHP	product design
2020	Öztürk & Paksoy	Interval type-2 fuzzy	green supplier selection
2021	Chen et al.	Grey fuzzy AHP	subcontractor selection
2021	Li & Zhang	Intuitionistic fuzzy AHP	product development
2022	Porto de Lima et al.	Hesitant fuzzy AHP	packaging design selection
2022	Karasan et al.	Neutrosophic AHP	customer-oriented product design
2023	Baskir	Interval type-2 fuzzy AHP	lean after-sales service evaluation in the automotive industry
2023	Wang	Interval valued fuzzy AHP	port sustainability evaluation
2023	Ayyildiz et al.	Interval valued pythagorean fuzzy AHP	hazelnut production evaluation

3.1.3. Index-based Evaluation Approach

An index, although directly related to mathematical calculations, is a statistical measure that shows the changes of a variable or group of variables over time or space. It is also defined as a measure that indicates the state of a system in a particular subject. In this context, index-based evaluations are made to determine the state of the system.

There are many studies in the literature dealing with index-based assessments in many different fields. In this thesis, evaluation indices in the field of education are examined.

These studies are summarized in Table 3.2 in terms of aim of the study, integrated methods and education type.

Table 3.2: Papers concerning education evaluation index

Year	Author	Aim of the study	Integrated methods	Education type
2006	Zeng et al.	to present a classroom-teaching quality system	AHP	higher education
2010	Du	to determine the weight of industry-university cooperation education quality	AHP	higher education
2013	Lijuan & Meng	to present the evaluation index system	-	higher education
2013	Tang	to construct the evaluation index system	-	higher vocational education
2013	Zhu	to design of entrepreneurship education service quality	QFD	entrepreneurship education
2015	Wu	to propose a teaching quality evaluation system	Grey clustering analysis	physical education
2016	Tang & Zhou	to construct the evaluation index system of practical teaching quality	-	higher vocational education
2016	Bao	to present the course quality evaluation index	-	higher vocational education
2016	Weng	to present the evaluation index system	-	higher education
2016	Huang et al.	to present the evaluation index system against cloud environment	-	higher education

Table 3.2: Papers concerning education evaluation index (*continue*)

Year	Author	Aim of the study	Integrated methods	Education type
2016	Peng & Han	to establish the evaluation index of the quality system in the armed police academy	AHP	political education
2016	Ye et al.	to present the evaluation index system for e-government performance	AHP	higher education
2017	Shi & Wang	to present the evaluation index system	AHP	secondary education
2018	Wu	to present improved performance evaluation index system and fuzzy evaluation model	Fuzzy theory	political education
2019	Xu & Rappaport	to construct the teaching evaluation index system	-	physical education
2021	Huang & Zhang	to construct the project-based learning evaluation index system	-	music education
2021	Su et al.	to conduct an in-depth analysis of learners' scientific, technical, engineering, artistic, and mathematical literacy	-	STEAM education
2021	Wang et al.	to present the evaluation index system	-	physical education
2021	Zhao & Gudamu	to rank teaching evaluation index system	AHP	physical education
2021	Wei et al.	to present the evaluation index system for education quality	AHP	postgraduate education

Table 3.2: Papers concerning education evaluation index (*continue*)

Year	Author	Aim of the study	Integrated methods	Education type
2021	Yang et al.	to present the evaluation index system based on multi-source information fusion	-	higher education
2022	Wang	to analyze the feasibility of the fuzzy comprehensive evaluation method in social work evaluation	AHP – fuzzy theory	health education
2022	Tian et al.	to present the evaluation index system	-	physical education
2022	Fang	to present the evaluation index and analyze wearable devices	-	physical education
2022	Wang & Xu	to construct the teaching evaluation index system	-	physical education
2022	Fu et al.	to present the tab analysis of evaluation index	Fuzzy theory	art education

The studies given in Table 3.2 have been increasing especially in the last two years. In these studies, some methods such as AHP, grey clustering analysis, fuzzy theory, and QFD are used. In terms of education type, studies are mostly conducted in the field of higher education.

3.2. Used Technique: Fermatean Fuzzy Sets

3.2.1. Preliminaries of Fermatean Fuzzy Sets

Yager (2016) defined a broader class of these sets as q -rung ortho-pair fuzzy sets, in which the sum of the q^{th} power of the support for and the q^{th} power of the support against is bonded by one. He observed that when q grows, the universe of admissible

ortho-pairs expands, giving the user more flexibility in expressing their view regarding membership grade.

Yager (2013) interpreted q-rung orthopair fuzzy sets as Pythagorean fuzzy sets for $q = 2$. Senapati and Yager (2020) consider q-rung orthopair fuzzy sets to be FFSs when $q = 3$.

Definition 1 (Senapati & Yager, 2020): Suppose X represents the universe of discourse. An FFS $\mathcal{F}$ in X is an object having the form:

$$\mathcal{F} = \{\langle x, \alpha_{\mathcal{F}}(x), \beta_{\mathcal{F}}(x) \rangle : x \in X\} \quad (3.2.1)$$

where $\alpha_{\mathcal{F}}(x) : \mathcal{F} \rightarrow [0,1]$ and $\beta_{\mathcal{F}}(x) : \mathcal{F} \rightarrow [0,1]$. $\alpha_{\mathcal{F}}(x)$ and $\beta_{\mathcal{F}}(x)$ are the membership and non-membership degrees of each element $x \in X$ in the set $\mathcal{F}$, including the condition $0 \leq (\alpha_{\mathcal{F}}(x))^3 + (\beta_{\mathcal{F}}(x))^3 \leq 1$.

For an FFS $\mathcal{F}$ and $x \in X$,

$$\tau = \sqrt[3]{1 - (\alpha_{\mathcal{F}}(x))^3 - (\beta_{\mathcal{F}}(x))^3} \quad (3.2.2)$$

means the degree of indeterminacy of x to $\mathcal{F}$.

Definition 2 (Senapati & Yager, 2020): For three FFS $\mathcal{F} = \langle \alpha_{\mathcal{F}}, \beta_{\mathcal{F}} \rangle$, $\mathcal{F}_1 = \langle \alpha_{F_1}, \beta_{F_1} \rangle$, and $\mathcal{F}_2 = \langle \alpha_{F_2}, \beta_{F_2} \rangle$, ε is a positive real number, the following ones are valid:

$$(i) \mathcal{F}_1 \oplus \mathcal{F}_2 = \langle \sqrt[3]{\alpha_{F_1}^3 + \alpha_{F_2}^3 - \alpha_{F_1}^3 \alpha_{F_2}^3}, \beta_{F_1} \beta_{F_2} \rangle$$

$$(ii) \mathcal{F}_1 \otimes \mathcal{F}_2 = \langle \alpha_{F_1} \alpha_{F_2}, \sqrt[3]{\beta_{F_1}^3 + \beta_{F_2}^3 - \beta_{F_1}^3 \beta_{F_2}^3} \rangle$$

$$(iii) \varepsilon \mathcal{F} = \langle \sqrt[3]{1 - (1 - \alpha_{\mathcal{F}}^3)^\varepsilon}, \beta_{\mathcal{F}}^\varepsilon \rangle$$

$$(iv) \mathcal{F}^\varepsilon = \langle \alpha_F^\varepsilon, \sqrt[3]{1 - (1 - \beta_F^3)^\varepsilon} \rangle$$

$$(v) \mathcal{F}^c = \langle \beta_F, \alpha_F \rangle.$$

Definition 3 (Senapati & Yager, 2020): For any FFS $\mathcal{F} = \langle \alpha_F, \beta_F \rangle$, the score and accuracy functions of $\mathcal{F}$ can be represented as:

$$sco(\mathcal{F}) = \alpha_F^3 - \beta_F^3 \quad (3.2.3)$$

$$acc(\mathcal{F}) = \alpha_F^3 + \beta_F^3 \quad (3.2.4)$$

3.2.2. Aggregation Operators for Fermatean Fuzzy Sets

In a realistic decision-making environment, human vision is unpredictable and unintelligible, and aggregation operators capture the association between data parameters. It enables us to extract compressed relevant data from a variety of sources.

The Dombi operator has a high degree of flexibility with a generic parameter (Du, 2020). There may not be a reciprocal relationship in every evaluation. In such cases, it may be necessary to group the criteria. The Partition Average operator is capable of integrating the parameter evaluation value from different groups with the identical aggregation method and aggregating the integration results of different groups with the arithmetic average operator (Yang et al., 2018). The Muirhead Mean operator is a typical adaptable addition operator that may capture complicated attribute correlations. The Muirhead Mean operator can handle multiple circumstances where not every attribute are linked, there are interrelationships between any two attributes, and there is a relationship between any three or more attributes by simply adjusting the value of the relevant parameter (Liu & Teng, 2018).

In our problem, there are many dimensions such as user-based, system-based, organizational-based, etc. Therefore, it is an evaluation group that should be divided

into several parts, and the evaluation information is given by the subjective opinions of the decision makers, so the flexibility of the integrated method is greatly required in the evaluation process. Therefore, an aggregation operator needs to be quite flexible not only in the format but also in dealing with the complex correlation between attributes. In this context, the Fermatean Fuzzy Dombi Weighted Partitioned Muirhead Mean (FFDWPM) is used in this study.

3.2.2.1. Fermatean Fuzzy Dombi Operator

For three FFS $\mathcal{F} = \langle \alpha_F, \beta_F \rangle$, $\mathcal{F}_1 = \langle \alpha_{F_1}, \beta_{F_1} \rangle$, and $\mathcal{F}_2 = \langle \alpha_{F_2}, \beta_{F_2} \rangle$, ε is a positive real number and $g \geq 0$. Following that, the fundamental operations of FFS in relation to Dombi operation are demonstrated in the following forms (Shit & Ghorai, 2021):

$$\begin{aligned}
 \text{(i) } \mathcal{F}_1 \oplus_{Dom} \mathcal{F}_2 &= \left(\sqrt[3]{1 - \frac{1}{1 + \left[\left(\frac{\alpha_{F_1}^3}{1 - \alpha_{F_1}^3} \right)^g + \left(\frac{\alpha_{F_2}^3}{1 - \alpha_{F_2}^3} \right)^g \right]^{\frac{1}{g}}}}, \sqrt[3]{\frac{1}{1 + \left[\left(\frac{1 - \beta_{F_1}^3}{\beta_{F_1}^3} \right)^g + \left(\frac{1 - \beta_{F_2}^3}{\beta_{F_2}^3} \right)^g \right]^{\frac{1}{g}}}} \right) \\
 \text{(ii) } \mathcal{F}_1 \otimes_{Dom} \mathcal{F}_2 &= \left(\sqrt[3]{\frac{1}{1 + \left[\left(\frac{1 - \alpha_{F_1}^3}{\alpha_{F_1}^3} \right)^g + \left(\frac{1 - \alpha_{F_2}^3}{\alpha_{F_2}^3} \right)^g \right]^{\frac{1}{g}}}}, \sqrt[3]{1 - \frac{1}{1 + \left[\left(\frac{\beta_{F_1}^3}{1 - \beta_{F_1}^3} \right)^g + \left(\frac{\beta_{F_2}^3}{1 - \beta_{F_2}^3} \right)^g \right]^{\frac{1}{g}}}} \right) \\
 \text{(iii) } (\varepsilon \mathcal{F})_{Dom} &= \left(\sqrt[3]{1 - \frac{1}{1 + \left[\varepsilon \left(\frac{\alpha_F^3}{1 - \alpha_F^3} \right)^g \right]^{\frac{1}{g}}}}, \sqrt[3]{\frac{1}{1 + \left[\varepsilon \left(\frac{1 - \beta_F^3}{\beta_F^3} \right)^g \right]^{\frac{1}{g}}}} \right) \\
 \text{(iv) } (\mathcal{F}^\varepsilon)_{Dom} &= \left(\sqrt[3]{\frac{1}{1 + \left[\varepsilon \left(\frac{1 - \alpha_F^3}{\alpha_F^3} \right)^g \right]^{\frac{1}{g}}}}, \sqrt[3]{1 - \frac{1}{1 + \left[\varepsilon \left(\frac{\beta_F^3}{1 - \beta_F^3} \right)^g \right]^{\frac{1}{g}}}} \right)
 \end{aligned}$$

3.2.2.2. Partitioned Muirhead Mean Operator

The relationships between various polymerized factors in the internal structure are expressed by the Muirhead Mean operator. The attributes are divided into different subregions using this operator. In the homogenous subdomain, attributes refer to the interrelationships between distinct arguments, whereas in other subdomains, they stand alone.

The partition Bonferroni Mean operator can capture the relationship of any two attributes in the homogeneous subdomain, while the partition Maclaurin Symmetric Mean section operator can identify the relationship between multiple attributes in the homogeneous subdomain. This study uses the partition Muirhead Mean (PMM) operator, which is a general form of these two operators, to explain the practical correlation between criteria. It is defined mathematically as follows (Zeng et al., 2022).

Definition 4 (Qin et al., 2019): $S = \{r_1, r_2, r_3, \dots, r_n\}$ is the set of non-negative numbers. $S_h = \{r_1, r_2, r_3, \dots, r_{|S_h|}\}$ ($h = 1, 2, 3, \dots, N$) is N subdomains of S , with the $S_1 \cup S_2 \cup S_3 \cup \dots \cup S_N = S$, and $S_1 \cap S_2 \cap S_3 \cap \dots \cap S_N = \emptyset$. Then, the PMM is given in the following form:

$$PMM^V(r_1, r_2, r_3, \dots, r_n) = \frac{1}{N} \sum_{h=1}^N \left(\frac{1}{|S_h|!} \sum_{b \in B_{|S_h|}} \prod_{i_h=1}^{|S_h|} r_{b(i_h)}^{v_{i_h}} \right)^{\frac{1}{\sum_{i_h=1}^{|S_h|} v_{i_h}}} \quad (3.2.5)$$

3.2.2.3. Fermatean Fuzzy Dombi Weighted Partitioned Muirhead Mean Operator

The FFDWPMO operator provides generality and flexibility both in form and in the aggregation process and handles various related situations within attributes flexibly, including the independence of all multiple attributes.

Definition 5 (Zeng et al., 2022): $\mathcal{F} = \{\langle x, \alpha_F(x), \beta_F(x) \rangle : x \in X\}$ is a class of FFS, and $V = (v_1, v_2, v_3, \dots, v_n)$ determines a collection of n real numbers with $v_1, v_2, v_3, \dots, v_n \geq 0$ but not concurrently $v_1 = v_2 = v_3 = \dots = v_n = 0$.

$w = (w_1, w_2, w_3, \dots, w_n)^T$ is the weight vector relative to $\mathcal{F}_i$, $i = 1, 2, 3, \dots, n$ with $w_i \geq 0$ and $\sum_{i=1}^n w_i = 1$. Then, FFDWPMM operator is presented in the following form:

$$FFDWPM^V(\mathcal{F}_1, \mathcal{F}_2, \mathcal{F}_3, \dots, \mathcal{F}_n) = \left\{ \frac{1}{N} \sum_{h=1}^N \left(\frac{1}{|S_h|!} \sum_{b \in B_{|S_h|}} \prod_{i_h=1}^{|S_h|} w_{b(i_h)} \mathcal{F}_{b(i_h)}^{v_{i_h}} \right)^{\frac{1}{\sum_{i_h=1}^{|S_h|} v_{i_h}}} \right\}_{Dom} \quad (3.2.6)$$

where $S = \{r_1, r_2, r_3, \dots, r_n\}$ is the set, $S_h = \{r_1, r_2, r_3, \dots, r_{|S_h|}\}$ ($h = 1, 2, 3, \dots, N$) is N subdomains of S , with the $S_1 \cup S_2 \cup S_3 \cup \dots \cup S_N = S$, and $S_1 \cap S_2 \cap S_3 \cap \dots \cap S_N = \emptyset$. $|S_h|$ is the number of arguments in the partition $S_h = \{r_1, r_2, r_3, \dots, r_{|S_h|}\}$ ($h = 1, 2, 3, \dots, N$). $b_{(i_h)}$ is any permutation of $(1, 2, \dots, |S_h|)$, and $B_{|S_h|}$ is the convergence of all permutations of $(1, 2, \dots, |S_h|)$.

3.3. Used Methods: Fermatean Fuzzy MCDM

3.3.1. Fermatean Fuzzy DEMATEL Method

The DEMATEL method was first developed in 1972 by the Science and Human Relations Program of the Battelle Memorial Institute in Geneva (Gabus & Fontela, 1972). With this method, complex cause-and-effect relationships between all factors affecting a decision problem can be easily identified and analyzed (Huang et al., 2007; Shieh et al., 2010).

The DEMATEL is a method used to analyze different factors affecting a system and to understand the relationships between these factors better. This method, based on graph theory, enables problems to be solved and analyzed with visualization techniques (Tzeng et al., 2007). The DEMATEL method can prioritize factors in terms of the type of relationships and the importance of their influence on each other. Thus, the criteria that have more influence on other factors and are considered to have a high priority are called cause criteria, while the criteria that have more influence and are considered to

have a low priority are called outcome criteria (Chang et al., 2011; Büyüközkan & Çifçi, 2012).

The DEMATEL method is one of the most effective methods used especially in solving complex and intertwined problem groups. Since the method can be applied to multi-criteria decision problems in different fields, there are many studies on DEMATEL and advanced fuzzy DEMATEL methods in the literature. With the DEMATEL method, it is possible to visualize the complex cause and effect relationships between factors, but it is very difficult to quantitatively express the interaction between factors. For this reason, the DEMATEL method is extended to the fuzzy environment to determine the degree of interaction between factors (Wu & Lee, 2007; Büyüközkan & Çifçi, 2012; Büyüközkan et al., 2017).

In this thesis, the DEMATEL method is integrated with the fermatean fuzzy approach to define the relationship between the criteria more flexibly and to provide a more comfortable decision environment for the evaluating experts. There are two studies in the literature using the fermatean fuzzy DEMATEL method. Gonzales et al. (2022) presented the methodological extension of DEMATEL method with fermatean fuzzy sets for modelling the barriers of implementing education 4.0. The comprehensive framework including rough fermatean DEMATEL approach is proposed by Kao et al. (2022) for sustainable development evaluation for the manufacturing industry.

DEMATEL allows to plan and solve problems by dividing the relevant factors into cause and effect groups that will provide a better understanding of the causal relationship. Criteria that have more influence on other criteria and are considered to be of high priority are called cause criteria; criteria that are more influential and are considered to be of low priority are called consequence criteria (Büyüközkan & Çifçi, 2012; Gonzales et al., 2022).

3.3.2. Fermatean Fuzzy MACONT Method

Wen et al. proposed the MACONT in 2020. Unlike many MCDM systems, this one employs various normalization techniques and hybrid aggregation procedures at the same time. The aims of this method are:

- use three normalization techniques to normalize the performance values of the alternatives over the criteria,
- create a composite of three normalized performance values,
- define a virtual reference alternative,
- combine the weights of the criteria by integrating the distances between each option and the reference alternative using two mixed aggregation operators,
- compute the alternatives' final comprehensive scores based on the integration of the subordinate comprehensive scores generated by two mixed aggregation operators,
- and sort the alternatives according to the final comprehensive scores.

As this method is relatively recently developed, there are not many publications on this method. The studies in the literature that present the MACONT method are shown in Table 3.3.

As seen in Table 3.3, the MACONT method is integrated with only two different methods (i.e. CEBOM and e-STEP) in the literature. In addition, there is no study integrating this method with advanced fuzzy approaches. This method is used in many different fields such as sustainable third-party reverse logistics provider selection, pension service institution selection, transportation budget allocation, quality evaluation of industry-education integration, and sustainable management of end-of-life tires evaluation. In this thesis, MACONT method is integrated with fermatean fuzzy approach and used in the evaluation of digital education platforms.

Table 3.3: Papers concerning MACONT method

Year	Author	Integrated methods	Application area
2020	Wen et al.	-	sustainable third-party reverse logistics provider selection
2021	Wen & Liao	-	pension service institution selection
2023	Truong & Li	e-STEP	transportation budget allocation
2023	Huang & Chen	-	quality evaluation of industry-education integration
2023	Wen & Liao	-	-
2023	Nguyen	-	logistics provider selection
2023	Simic et al.	CEBOM	sustainable management of end-of-life tires evaluation

3.3.3. Fermatean Fuzzy AHP Method

AHP is a quantitative decision analysis method for qualitative problems first introduced by Saaty (1980). The feature that makes the AHP method superior to other methods is that it is a method that includes qualitative and quantitative elements in the study. Its application area is wide and it is used in solving complex problems. It is preferred more than other methods in terms of including objective and subjective opinions in the process and making group decisions.

In the literature, the AHP method has been used for many studies such as the best personnel selection, location selection, meeting area determination, supplier selection. The integration of this method with the fermatean fuzzy approach is very new in the literature. Firstly, Camci et al. (2022) proposed fermatean fuzzy AHP for supplier selection. The fermatean fuzzy AHP is applied for evaluation of the online teaching quality by Zeng et al. (2022). Alkan and Kahraman (2023) integrated AHP method with interval-valued fermatean fuzzy approach. Karuppiah and Sankaranarayanan (2023) presented fermatean fuzzy AHP method with DEMATEL and TOPSIS methods for evaluation of the e-waste mitigation strategies.

In this thesis, the fermatean fuzzy AHP method based on an aggregator operator with the QFD approach is used.

3.3.4. Fermatean Fuzzy PIPRECIA Method

The classical PIPRECIA method is one of the MCDM methods developed by Stanujkic et al. (2017). The PIPRECIA method is a method developed due to some difficulties of the Step-wise Weight Assessment Ratio Analysis (SWARA) method. This method provides more meaningful results when the number of decision makers and criteria are high, thanks to its mathematical calculations. It is one of the preferred methods since there is no need to determine the order of importance when determining the criterion weights. The integration of this method with the fuzzy approach has been proposed by Stević et al. (2018).

The studies in the literature that present the PIPRECIA method and fuzzy or advanced fuzzy logic approach are shown in Table 3.4.

Table 3.4: Papers concerning fuzzy/advanced fuzzy PIPRECIA method

Year	Author	Fuzzy/Advanced fuzzy PIPRECIA	Integrated methods	Application area
2018	Stević et al.	fuzzy PIPRECIA	SWOT analysis	evaluation of conditions for the implementation of IT
2020	Đalić et al.	fuzzy PIPRECIA	SWOT analysis	analysis of logistics performances
2020	Tomašević et al.	fuzzy PIPRECIA	-	performance evaluation
2020	Vesković et al.	fuzzy PIPRECIA	fuzzy EDAS	selection of solution for business balance of passenger rail operator
2020	Blagojević et al.	fuzzy PIPRECIA	DEA	evaluation of safety in railway traffic

Table 3.4: Papers concerning fuzzy/advanced fuzzy PIPRECIA method (*continue*)

Year	Author	Fuzzy/Advanced fuzzy PIPRECIA	Integrated methods	Application area
2021	Bakır et al.	fuzzy PIPRECIA	fuzzy MARCOS	regional aircraft selection
2021	Ulutaş et al.	fuzzy PIPRECIA	fuzzy PSI – fuzzy COCOSO	transportation company selection
2022	Stević et al.	fuzzy PIPRECIA	Delphi method	evaluation of dimensions of quality model
2022	Stević et al.	fuzzy PIPRECIA	-	evaluation of causes of delays in the road construction projects
2023	Xu et al.	trapezoidal interval type-2 fuzzy PIPRECIA	trapezoidal interval type-2 fuzzy MARCOS	efficiency management of traffic flow

As can be seen in Table 3.4, the relatively new PIPRECIA method is generally used together with the fuzzy approach in the literature. There is only one study in the literature that uses the advanced fuzzy logic approach (Xu et al., 2023). In order to fill this gap in the literature, this thesis uses the PIPRECIA method together with the fermatean fuzzy approach.

3.4. Computational Steps of Proposed Approaches

3.4.1. Computational Steps of the Integrated Fermatean Fuzzy DEMATEL - MACONT Approach

The steps of the proposed integrated fermatean fuzzy DEMATEL-MACONT methodology are as follows:

Step 1: A pairwise comparison matrices are constructed by DMs with the linguistic scale in Table 3.5.

Step 2: These pairwise matrices obtained from the DMs are combined using the arithmetic mean and fermatean fuzzy operations.

Table 3.5: Linguistic scale for fermatean fuzzy DEMATEL (Gonzales et al., 2022)

Linguistic expressions	Fermaten fuzzy numbers
No Influence (NO)	(0,00;0,10)
Very low (VL)	(0,10;0,75)
Low (L)	(0,40;0,50)
High (H)	(0,70;0,20)
Very high (VH)	(0,90;0,10)

Step 3: The fermatean fuzzy numbers in the combined pairwise matrix are converted to crisp numbers with:

$$S(\mathcal{F}) = \frac{1}{2} \left[(\alpha_F(x))^3 - (\beta_F(x))^3 - \ln(1 + (\tau_F)^3) \right] \quad (3.4.1)$$

and $A = [a_{ij}]$ direct-relation matrix is formed.

Step 4: Based on the direct-relation matrix, the normalized direct-relation matrix (M) is obtained using the smallest value (k) in row and column. The main diagonal values in the direct-relation matrix are 0.

$$M = k \times A \quad (3.4.2)$$

$$k = \text{Min} \left\{ \frac{1}{\max \sum_{j=1}^n |a_{ij}|}, \frac{1}{\max \sum_{i=1}^n |a_{ij}|} \right\} \quad (3.4.3)$$

Step 5: The total-relation matrix is established by using:

$$T = M(I - M)^{-1} \quad (3.4.4)$$

Step 6: The sum of the rows (D) and the sum of the columns (R) are calculated and categorize the criteria into cause and effect group.

$$D = \sum_{j=1}^n t_{ij} \quad (3.4.5)$$

$$R = \sum_{i=1}^n t_{ij} \quad (3.4.6)$$

The prominence value of each factor is derived using the (D+R) value. Similarly, the factors are classified into cause and effect groups using (D-R).

The impact-diagraph map is constructed with (D+R) and (D-R) values. Here, the horizontal axis shows D+R and the vertical axis shows D-R. To have a suitable diagram, DMs need to set an impact level threshold. The threshold value is found by averaging the values in the total impact matrix.

Step 7: The influential weights of the criteria are computed as:

$$w_j = \sqrt{(D_j + R_j)^2 + (D_j - R_j)^2} \quad (3.4.7)$$

Then the weights are normalized by using:

$$w = \frac{w_j}{\sum_{j=1}^n w_j} \quad (3.4.8)$$

Step 8: A decision matrix is created between alternatives and criteria by using the linguistic scale in Table 3.6.

Step 9: These fermatean fuzzy numbers are converted to crisp numbers with:

$$S(\mathcal{F}) = \frac{1}{2} \left[(\alpha_{\mathcal{F}}(x))^3 - (\beta_{\mathcal{F}}(x))^3 - \ln(1 + (\tau_{\mathcal{F}})^3) \right] \quad (3.4.9)$$

and $X = [x_{ij}]$ matrix is formed.

Table 3.6: Linguistic scale for fermatean fuzzy MCDM methods (Rani & Mishra, 2021)

Linguistic expressions	Fermaten fuzzy numbers
Absolutely high (AH)	(0.95;0.20)
Very high (VH)	(0.90;0.40)
High (H)	(0.80;0.50)
Medium high (MH)	(0.75;0.60)
Average (A)	(0.60;0.70)
Medium low (ML)	(0.50;0.80)
Low (L)	(0.40;0.85)
Very low (VL)	(0.30;0.90)
Absolutely low (AL)	(0.20;0.95)

Step 10. Three different normalization techniques are applied to create the normalized decision matrix.

Type-1 normalization is calculated as

$$\hat{x}_{ij}^1 = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \text{ for benefit criteria} \quad (3.4.10)$$

$$\hat{x}_{ij}^1 = \frac{\frac{1}{x_{ij}}}{\sum_{i=1}^m \frac{1}{x_{ij}}} \text{ for cost criteria} \quad (3.4.11)$$

Type-2 normalization is calculated as

$$\hat{x}_{ij}^2 = \frac{x_{ij}}{\max_i x_{ij}} \text{ for benefit criteria} \quad (3.4.12)$$

$$\hat{x}_{ij}^2 = \frac{\min_i x_{ij}}{x_{ij}} \text{ for cost criteria} \quad (3.4.13)$$

Type-3 normalization is calculated as

$$\hat{x}_{ij}^3 = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \text{ for benefit criteria} \quad (3.4.14)$$

$$\hat{x}_{ij}^3 = \frac{x_{ij} - \max_i x_{ij}}{\min_i x_{ij} - \max_i x_{ij}} \text{ for cost criteria} \quad (3.4.15)$$

The balance parameters as α and β are used to integrate these normalized performance values. Each performance value in the aggregated decision matrix is calculated as:

$$\hat{x}_{ij} = \hat{x}_{ij}^1 \alpha + \hat{x}_{ij}^2 \beta + \hat{x}_{ij}^3 (1 - \alpha - \beta) \quad (3.4.16)$$

where $0 \leq \alpha, \beta \leq 1$, and the values of these two balance parameters are determined by experts. If experts attach more importance to the performance of one alternative over the other alternatives, α is assigned a larger value, and if experts want to emphasize the best performance of alternatives, β is assigned a larger value. If the experts emphasize that there is a large difference between the alternatives, i.e. they emphasize the best performance of the alternatives but do not ignore the worst performance of the alternatives, smaller values are assigned to α and β . In this study, α and β will be taken as $1/3$.

Step 11: The average performance values $\bar{x}_j$ ($j = 1, 2, \dots, n$) of alternatives on each criterion are computed. Summation of weighted normalized decision matrix for each alternative (π_i), and product of weighted normalized decision matrix (Q_i) are calculated with

$$\pi_i = \sum_{j=1}^n w_j (\hat{x}_{ij} - \bar{x}_j) \quad (3.4.17)$$

$$Q_i = \frac{\prod_{\gamma=1}^n (\bar{x}_j - \hat{x}_{ij})^{w_j}}{\prod_{\sigma=1}^n (\hat{x}_{ij} - \bar{x}_j)^{w_j}} \quad (3.4.18)$$

where γ represents the part of criteria that satisfy $\hat{x}_{ij} < \bar{x}_j$, and σ represents the part of criteria that satisfy $\bar{x}_j \leq \hat{x}_{ij}$.

Step 12. Two mixed aggregation scores are calculated as:

$$M_{i1} = \tau \frac{\pi_i}{\sqrt{\sum_{i=1}^m (\pi_i)^2}} + (1 - \tau) \frac{Q_i}{\sqrt{\sum_{i=1}^m (Q_i)^2}}, i = 1, 2, \dots, m \quad (3.4.19)$$

$$M_{i2} = \vartheta \max_j (w_j (\hat{x}_{ij} - \bar{x}_j)) + (1 - \vartheta) \min_j (w_j (\hat{x}_{ij} - \bar{x}_j)), i = 1, 2, \dots, m \quad (3.4.20)$$

In this study, τ and ϑ will be taken as 1/2.

Step 13. The final aggregated score of each alternative (M_i) is computed as

$$M_i = \frac{1}{2} \left(M_{i1} + \frac{M_{i2}}{\sqrt{\sum_{i=1}^m (M_{i2})^2}} \right), i = 1, 2, \dots, m \quad (3.4.21)$$

The alternative with the highest M_i value is identified as the best.

3.4.2. Computational Steps of the Fermatean Fuzzy QFD Approach with Fermatean Fuzzy AHP

In this thesis, the integrated fermatean fuzzy AHP based QFD methodology with aggregation operators for digital technology assessment in metaverse-based education is proposed. The essential steps of the proposed methodology are as follows:

Step 1: A model with the hierarchical structure including URs is created. The appropriate hierarchical structure model is built based on the influencing variables and internal logical linkages of the evaluation component.

Step 2. The pairwise comparison matrix is constructed by experts with linguistic scale in Table 3.6.

Step 3. These linguistic expressions are converted to crisp numbers with:

$$S(\mathcal{F}) = \frac{1}{2} \left[(\alpha_F(x))^3 - (\beta_F(x))^3 - \ln(1 + (\tau_F)^3) \right] \quad (3.4.22)$$

Step 4: The converted pairwise comparison matrix $P = [\phi_{ij}]_{n \times n}$ is structured. $\phi_{ij}(i, j = 1, 2, 3, \dots, n)$ is the relative importance scale of criteria c_i to criteria c_j , applying experienced experts' judgment information.

Step 5: The maximum eigenvalue of judgment λ_{max} is calculated with:

$$\psi_i = \prod_{j=1}^n \phi_{ij} \quad (i, j = 1, 2, 3, \dots, n) \quad (3.4.23)$$

$$w_i = \frac{\xi_i}{\sum_i^n \xi_i}, \quad \xi_i = \sqrt[n]{\psi_i} \quad (3.4.24)$$

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^n \frac{(Pw)_i}{w_i} \quad (3.4.25)$$

Step 6: The following equations are used to calculate the consistency of each pairwise comparison matrix:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3.4.26)$$

$$CR = \frac{CI}{RI} \quad (3.4.27)$$

The greater the consistency level, the lower the value of the consistency index (CI). To determine if the judgment matrix fits the criterion, compare the consistency ratio (CR) with the random consistency index (RI).

Step 7: The weights of the main URs are obtained using the arithmetic mean. And, these steps are applied for each sub-URs, and global weights are calculated by multiplying the weight of the main URs.

Step 8: The fermatean fuzzy evaluation matrix $R = [\mathcal{F}_{xy}]_{m \times n}$ between URs and TRs is created with linguistic expression in Table 3.6, where $\mathcal{F}_{xy} = \langle \alpha_{F_{xy}}, \beta_{F_{xy}} \rangle$ ($x = 1, 2, \dots, m; y = 1, 2, \dots, n$) determines FFS on the evaluation information of alternative $FA_x (x = 1, 2, \dots, m)$ with regard to criteria $c_y (y = 1, 2, \dots, n)$. If there was no link between the URs and TRs, the cell was left blank, suggesting that changing one did not impact the other.

Step 9: The fermatean fuzzy evaluation matrix is normalized. If c_y is benefit criteria, then $R = [\mathcal{F}_{xy}]_{m \times n} = [\alpha_{F_{xy}}, \beta_{F_{xy}}]_{m \times n}$. If c_y is cost criteria, then $R = [\mathcal{F}_{xy}]_{m \times n} = [\beta_{F_{xy}}, \alpha_{F_{xy}}]_{m \times n}$.

Step 10: The comprehensive assessment value $\Gamma_{A_x} (x = 1, 2, \dots, m)$ of each TRs is calculated. Utilizing the weight vector of URs obtained by Step 7, and matrix $R = [\mathcal{F}_{xy}]_{m \times n}$, computing the comprehensive assessment value of each TRs $FA_x (x = 1, 2, \dots, m)$ by utilizing the FFDWPM operator defined in equation (3.2.6).

Step 11: The TRs are ranked by the score value of the comprehensive evaluation value.

3.4.3. Computational Steps of the DETI Approach with Fermatean Fuzzy PIPRECIA

In this thesis, the integrated fermatean fuzzy PIPRECIA-DETI methodology for is proposed. The essential steps of the proposed methodology are as follows:

Step 1: First, the criteria (C_j) to be evaluated are determined.

Step 2: The degree of importance of the criterion relative to the other criterion in the next row is determined by the DMs using the linguistic expressions in Table 3.6.

The relative importance value is calculated as in (3.4.28):

$$s_j^{\mathcal{F}} = \begin{cases} > 1 & \text{if } C_j > C_{j-1} \\ = 1 & \text{if } C_j = C_{j-1} \\ < 1 & \text{if } C_j < C_{j-1} \end{cases} \quad (3.4.28)$$

In this way, the evaluations received from each DM are combined with the geometric mean.

Step 3: These fermatean fuzzy numbers are converted to crisp numbers with:

$$S(\mathcal{F}) = \frac{1}{2} \left[(\alpha_{\mathcal{F}}(x))^3 - (\beta_{\mathcal{F}}(x))^3 - \ln(1 + (\tau_{\mathcal{F}})^3) \right] \quad (3.4.29)$$

and s_j matrix is formed.

Step 4: The coefficient k_j is calculated using the combined values reflecting DMs' opinions.

$$k_j = \begin{cases} 1 & \text{if } j = 1 \\ 2 - s_j & \text{if } j > 1 \end{cases} \quad (3.4.30)$$

Step 5: The weight q_j is calculated.

$$q_j = \begin{cases} 1 & \text{if } j = 1 \\ \frac{q_{j-1}}{k_j} & \text{if } j > 1 \end{cases} \quad (3.4.31)$$

Step 6: The relative weights are normalized using (3.4.32).

$$w_j = \frac{q_j}{\sum_{j=1}^n q_j} \quad (3.4.32)$$

Step 7: After the weights are calculated with the PIPRECIA method, the Inverse PIPRECIA process is initiated. The criteria are ranked from the last criterion to the first criterion and evaluated from the penultimate criterion to the next criterion by the DMs using the linguistic expressions in Table 3.6.

The inverse relative importance value is calculated as in (3.4.33):

$$s_j^{\mathcal{F}'} = \begin{cases} > 1 & \text{if } C_j > C_{j+1} \\ = 1 & \text{if } C_j = C_{j+1} \\ < 1 & \text{if } C_j < C_{j+1} \end{cases} \quad (3.4.33)$$

In this way, the evaluations received from each DM are combined with the geometric mean.

Step 8: These fermatean fuzzy numbers are converted to crisp numbers with (3.4.29) and s_j' matrix is formed.

Step 9: The coefficient k_j' is calculated using the combined values reflecting DMs' opinions.

$$k_j' = \begin{cases} 1 & \text{if } j = n \\ 2 - s_j' & \text{if } j > n \end{cases} \quad (3.4.34)$$

n denotes a total number of criteria.

Step 10: The inverse weight q_j' is calculated.

$$q_j' = \begin{cases} 1 & \text{if } j = n \\ \frac{q_{j+1}'}{k_j'} & \text{if } j > n \end{cases} \quad (3.4.35)$$

Step 11: The inverse relative weights are normalized with (3.5.36).

$$w_j' = \frac{q_j'}{\sum_{j=1}^n q_j'} \quad (3.4.36)$$

Step 12: The final weights of the criteria is calculated by averaging the weights calculated with PIPRECIA and Inverse PIPRECIA.

$$w_j'' = \frac{1}{2}(w_j + w_j') \quad (3.4.37)$$

Step 13: The consistency of the results obtained from the PIPRECIA and reverse PIPRECIA method is checked using Spearman and Pearson correlation coefficients.

The Spearman correlation coefficient is a non-parametric measure of ordinal correlation and is primarily used for data analysis. It measures the strength and direction of the relationship between two ordinal variables (Zar, 1972).

The Spearman Coefficient, ρ , can take a value between +1 and -1:

- A value of ρ of 1 means a perfect rank relationship.
- A value of ρ of 0 means that there is no relationship between ranks.
- A value of ρ of -1 means that there is a perfect negative relationship between the ranks.
- The closer the ρ value is to 0, the weaker the relationship between the two ranks.

Pearson's correlation coefficient is a statistical measure of the strength of the linear relationship between paired data. In simple terms, Pearson's correlation coefficient calculates the effect of a change in one variable when the other variable changes. The Pearson coefficient correlation has a high statistical significance. It looks at the relationship between two variables. It tries to draw a line through the data of two variables to show the relationship between them. This linear relationship can be positive or negative (Cohen, 2009).

In the second part of this methodology, the DETI is calculated using the weights obtained with the fermatean fuzzy PIPRECIA method.

Step 14: DETI is defined as:

$$DETI = f(C_1, \dots, C_N) \quad (3.4.38)$$

where $C_1, \dots, C_N$ are the key components for user-centered trustworthy digital education.

Step 15: At the first level, based on the key components presented, the evaluations are made and the $P(c_i)$ values for each component are calculated as:

$$P(c_i) = \frac{\sum_{j=1}^6 w_{cij} * P(c_{ij})}{\sum_{j=1}^6 w_{cij}} \quad (i=1, \dots, 5) \quad (3.4.39)$$

where w_{cij} , $i = (1, \dots, 5)$ and $j = (1, \dots, 6)$, is the weight of the sub-component and $P(c_{ij})$ is the performance degree of the digital education system in the specified component. The explicit form of ethical components can be written as follows:

$$\begin{aligned} P(\text{ethical}) = & (w_{c11} * P(\text{human agency and oversight}) + w_{c12} * \\ & P(\text{perception of ethics}) + w_{c13} * P(\text{ethical decision making}) + w_{c14} * \\ & P(\text{Privacy and data governance}) + w_{c15} * \\ & P(\text{Protection of human rights and intellectual property rights}) + w_{c16} * \\ & P(\text{Codes of conduct})) / (w_{c11} + w_{c12} + w_{c13} + w_{c14} + w_{c15} + w_{c16}) \end{aligned}$$

Step 16: At the second level, DETI is formulated as:

$$DETI = \sum_{i=1}^5 P(c_i) \quad (3.4.40)$$

The explicit form can be written as follows:

$$\begin{aligned} DETI = & P(\text{ethical}) + P(\text{beneficial}) + w_{c3} * P(\text{responsible}) + w_{c4} * \\ & P(\text{explainable}) + w_{c5} * P(\text{fair}) \end{aligned}$$

While determining the performance value of the component in the digital education evaluation model, the experts were asked to make an evaluation on a scale of 1-9. In the digital education system, 9 is given if the component is provided to a very high degree and 1 is given if it is provided to a very low degree.

Step 17: Based on the performance values, DETI is calculated and the status of the system is analyzed with the radar charts.



4. PROPOSED NEW DIGITAL EDUCATION PLATFORM EVALUATION APPROACH

This chapter of the thesis proposes a general approach for the evaluation of digital education platforms. The proposed framework consists of an evaluation model and the validation of the proposed model using integrated fermatean fuzzy DEMATEL-MACONT approach. This chapter contains four main sections as follows: literature review of digital education platforms, proposed digital education platforms evaluation model, application of the proposed methodology to a real case in a university, and results. Details concerning these sections are presented below.

4.1. Literature Review of Digital Education Platforms

Education 4.0 in digital education concept involves the future design and vision of learning. In the literature, there are many terms for Education 4.0. Our definition of Education 4.0 was not the first one, and the definition of the proposed concept of Education 4.0 is as follows:

Education 4.0 is a personalized approach to determining new ways to learn via the use of up-to-date technology, allowing students to study with a variety of resources depending on their skills, abilities, and intellectual levels utilizing digital technologies at anytime, anywhere, and on any device. Big data, learning analytics, and big data together help the development of customized and adaptive learning by focusing on how learning data may be acquired, analyzed, and directed towards better learning and teaching.

Digital education approach (Yanez et al., 2010; Puncreobutr, 2016; Hussin, 2018; Butt et al., 2020):

- aims to use digital technologies, personalized data, open-source content, and connectivity at the highest level.
- aims to raise creative and innovative individuals.
- supports individuals to keep up with the innovative age.
- helps the student to evolve in accordance with societal trends.
- encourages students to improve users' capacity to use new technology.

With the developing technologies, the educational preferences of students change and are shaped according to their habits. To meet the educational needs of students, up-to-date technologies should be integrated into education, and educators should be more creative in course design. Digital education platforms ensure that these needs are met.

Today, with the development of computer and internet technology, distance education platforms have emerged, and these platforms have entered a great development process. As a result of the development of distance education platforms, the necessity of determining a place for training, meetings, and interview activities has been eliminated. Distance education enables individuals with different disabilities to continue their education regardless of time and place (Korableva et al., 2019; Guerrero et al., 2021; Bakkum et al., 2021).

The most relevant studies on digital education and online platforms are examined in Table 4.1. It is observed that the number of studies conducted in 2015 and after has increased. Studies are divided according to platform types. These types are the platform for high school, the platform for higher education, the platform for primary education, the platform for secondary education, the public service platform, the open education platform, etc.

Table 4.1: Papers concerning digital education and online platforms

Year	Author(s)	Aim of the study	Platform application area
2006	Lin & Pan	to introduce the testing installations through the use of a scorm-based e-learning platform	High school
2011	Cheng et al.	to demonstrate the concept of a public service platform for digital education materials	Public service
2015	Koster et al.	to introduce an educator-centered digital teaching platform	Educator-centered digital teaching
2015	Yamawaki	to provide a platform	Sustainable learning
2016	Cardonha et al.	to help persons with disabilities get customized training	Personalized training
2016	Sizova & Ulyanova	to present massive open online courses platform	Museum studies
2017	Khasianov et al.	to present three agent platform	Higher education
2017	Karahoca et al.	to design a prototype model for autistic learners in early childhood	Language education
2017	Tew et al.	to provide additional assistance with adaptive sensing devices	Higher education
2018	Almasri et al.	to support education in war with digital platforms	Primary education
2019	Gillet et al.	to implement the digital education	Secondary education
2019	Korableva et al.	to provide a framework for researching two distinct mooc platforms	Open education
2019	Bruechner et al.	to create a framework for digital education	Secondary education

Table 4.1: Papers concerning digital education and online platforms (*continue*)

Year	Author(s)	Aim of the study	Platform application area
2019	Yadav et al.	to create a digital patient health hub	Personal health of patients
2019	Almasri et al.	to present a framework for monitored self-directed learning in emergency cases	Primary education
2019	Kirillovich et al.	to adopt corpus of educational mathematical texts to digital educational platform	Mathematical textbooks
2020	Pixley et al.	to explore the feasibility and usability of the platform	Oncology disease-specific
2020	Masneri et al.	to present a platform using augmented reality	Interactive education
2020	Ryabova & Yelnykova	to present the digital transformation for teachers' professional growth	Higher education
2020	Zhao et al.	to propose digital education crowdfunding and crowd creating platform development	Personalized education
2021	Decuypere & Landri	to present the ranking platform: u-multirank	General education
2021	Bakkum et al.	to develop digital educational resources for pharmaceutical sciences and medicines	Prescribing education
2021	Schlupeck et al.	to develop and evaluate an interactive online course for medical students	Online learning
2021	Leunig et al.	to present the difference between online and traditional discussion	Online learning
2021	DiGiacomo et al.	to present an online classroom application	Online learning
2022	Adem et al.	to determine the most appropriate distance learning platform	Online learning
2022	Liu	to present an adaptive learning platform	Primary education
2022	Pacheco-Velazquez	to evaluate the effectiveness of the platform by exploring the opinion of students	Logistics education

Table 4.1: Papers concerning digital education and online platforms (*continue*)

Year	Author(s)	Aim of the study	Platform application area
2023	Songkram et al.	to investigate students' behavioral intentions for a digital learning platform	Online learning
2023	Wang et al.	to present a question-answer generation system for a distance learning platform	Online learning
2023	Chambers et al.	to examine online medical education using a facebook peer-to-peer learning platform	Medical education

According to Table 4.1, there are studies on platforms in the field of digital education in the literature. However, there is no study evaluating the platforms used in synchronous education with analytical methods. In this study, digital education platforms are evaluated by using fermatean fuzzy MCDM methods.

Distance education platforms include learning in-group form in a virtual environment. It provides the opportunity to collaborate with individuals in different places with applications of virtual classroom tools such as voice and video communication, chat, desktop and application sharing, and white boarding. With the digital education platform, students and instructors can communicate live with each other in a virtual classroom environment. They can simultaneously ask questions, convey their requests regarding incomprehensible matters to the other party, and have the opportunity to discuss with each other (Cacheiro-Gonzalez et al., 2019; Chen et al., 2020; Schlupeck et al., 2021; Sidi et al., 2023).

The advantages of digital education platforms can be listed as follows (Bruechner et al., 2019; Cacheiro-Gonzalez et al., 2019; DiGiacomo et al., 2021; Sidi et al., 2023; Lamine et al., 2023):

- Supporting different learning methods
- Flexibility
- Access to more people, more data at the same time

- Eliminating geo-restrictions
- Cost eligibility
- Time flexibility
- Performance increase of students
- Measurable results and reporting
- Easy and flexible access
- Interactive education and gamification
- Instant feedback
- Standardization

4.2. Proposition of Digital Education Platform Evaluation Model

In this chapter, there are three parts that are illustrated in Figure 4.1: model proposition, fermatean fuzzy DEMATEL, and fermatean fuzzy MACONT. It is very important to choose the right platform that can meet the needs of the digital distance education model. For this, first of all, the demands for the platforms should be determined. Firstly, studies in the literature, industrial reports, experts' opinions, and student-academician opinions are examined. According to this examination, the expectations for the digital education platform are determined. In addition, the digital education platforms are identified with the literature review and expert opinions. In the second part, the importance degree of the expectations is calculated with the fermatean fuzzy DEMATEL method. In the last part, the digital education platforms are prioritized with the fermatean fuzzy MACONT method by using the steps in the flowchart of the methodology.

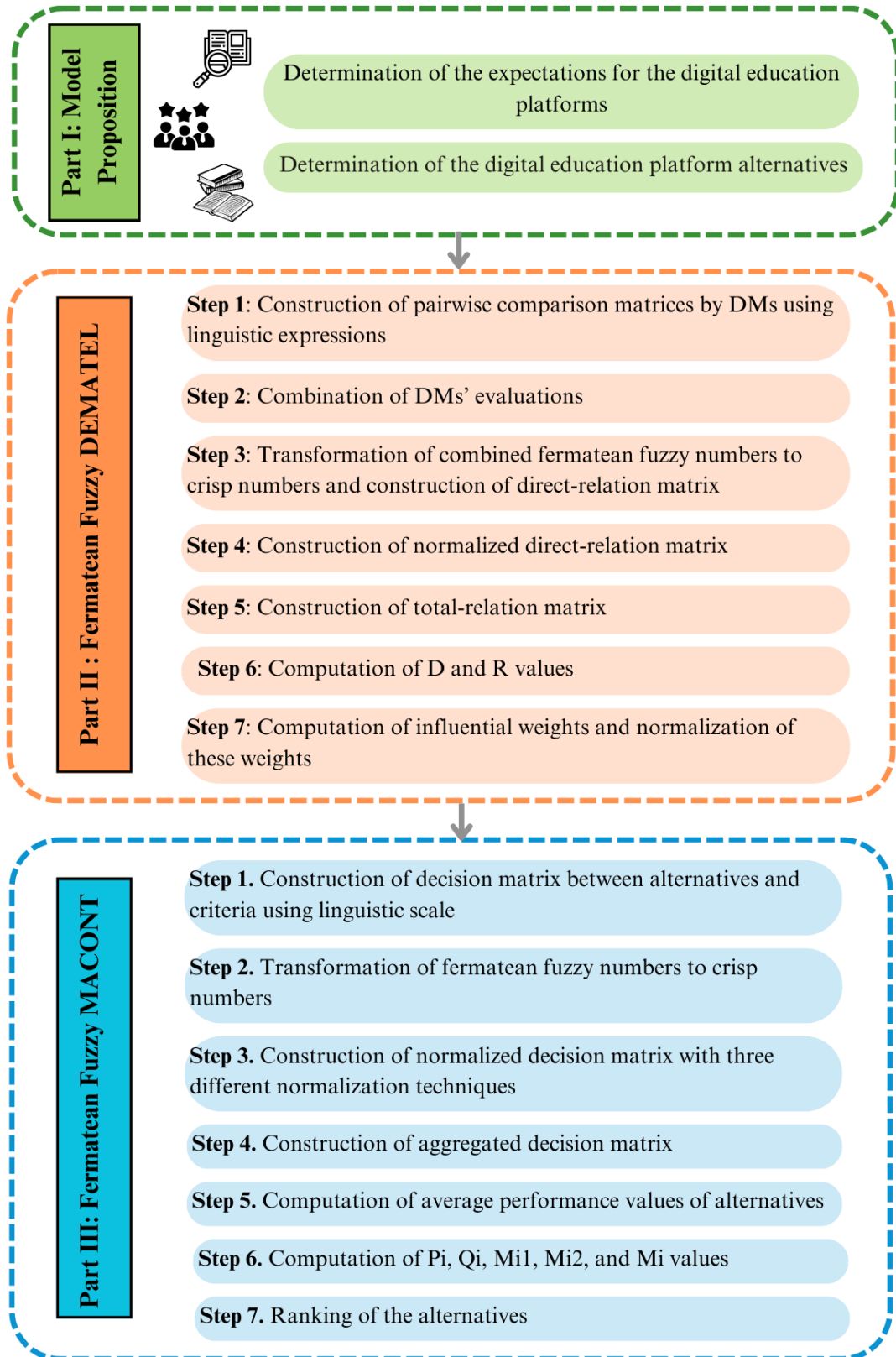


Figure 4.1: Flowchart of the proposed digital education platform evaluation approach

4.2.1. User Expectations of Digital Education Platform

Distance education is a systematic form of education where students and teachers are both in different places in the process of learning and teaching, providing individuality, flexibility, and independence in terms of space, time, and space. In its shortest definition, distance education is an economical and interactive education model that is realized by making use of technological tools and equipment regardless of time and place (Keegan, 1996).

With the development of technology, distance education opportunities have increased and many opportunities have emerged for the integration of individual and mass education methods into a single structure. In the pandemic period, applications have become widespread to take advantage of these opportunities (Chen et al., 2020).

It is stated that the most effective way to the digital infrastructure required for distance education is the system approach. Scientists indicate that future education is digital education. Developing software systems, providing adequate and necessary hardware, realizing policy-oriented harmonization, ensuring the prevalence of digitalization and technology, and keeping good reports on the impressions of these processes are among the first things to be completed (Liu et al., 2020).

The pandemic process has shown how important it is to have the infrastructure of distance education systems for universities. In other situations where education needs to be continued remotely, universities need to establish this infrastructure to ensure that the education is not interrupted, conduct lessons effectively, and continue education-training activities in a synchronized manner (Cacheiro-Gonzalez et al., 2019).

At this point, it is important to take the opinions of the students and academicians in addition to the solutions proposed by the state and to integrate a system suitable for them. It is also important for students to have the necessary equipment and a distance education system in terms of the continuous and synchronized execution of this process.

The aim of this is to ensure that each student continues to actively participate in distance education lessons and to make it sustainable.

In this context, a literature review is made while determining expectations for the digital distance education platform in this thesis. In addition, industrial reports on this subject are examined. Then, to obtain meaningful results, the opinions of a group of students and academicians about digital distance education platforms are obtained. As a result of these, expectations determined for the digital distance education platform are as in Table 4.2.



Table 4.2: Expectations for the digital education platforms

Expectations	Brief explanation	Sources
Technique/Infrastructure		
Easy-to-use platform and user interface	The interface required for the platform to be used comfortably by users.	Salavati (2016); Buasuwan (2018); Buzov (2020); <i>Student/Academicians view</i>
Large ecosystem of educational tools and services	The platform has a wide environment to cover all kinds of educational tools.	William Penn School District (2020); Aristin et al. (2020)
Equity and quality of access and infrastructure	The platform provides equal and quality service to all users in terms of infrastructure and accessibility.	European Commission Staff Working Document (2018); Aristin et al. (2020); <i>Student/Academicians view</i>
Capability to host large scale users	The platform has the infrastructure to handle small capacities.	Tiven et al. (2018); Waghid (2019); Qin et al. (2020); <i>Student/Academicians view</i>
System security	The platform protects personal data and privacy.	Tiven et al. (2018); Ciolacu et al. (2018); European Commission Staff Working Document (2018)

Table 4.2: Expectations for the digital education platforms (*continue*)

Expectations	Brief explanation	Sources
Digital Competency		
User-driven technology in tackling educational challenges	The technologies used in educational platforms are to prioritize student benefits and be pedagogical.	KPMG Report (2017); European Commission Staff Working Document (2018); <i>Student/Academicians view</i>
Digital technologies to support mobility	Digital technologies are required for the user to use the platform anywhere from the device they want.	Salavati (2016); European Commission Staff Working Document (2018); Ab Rahman et al. (2019)
Digital alignment and integration	Making digital technology ready and integrating it into the existing system.	Salavati (2016); Khasianov et al. (2017); <i>Student/Academicians view</i>
Digital skills	A combination of skills regarding the use of technology to meet the user's need on the platform, solve problems, communicate, manage information, create and share content effectively, appropriately, safely, and ethically.	European Commission Staff Working Document (2018); Sharma (2019); Aristin et al. (2020); <i>Student/Academicians view</i>
Digital customization	Providing user-specific services using digital technologies.	European Commission Staff Working Document (2018); <i>Student/Academicians view</i>

Table 4.2: Expectations for the digital education platforms (*continue*)

Expectations	Brief explanation	Sources
Functionality		
Adaptability & flexibility	The platform can be easily adapted to all kinds of issues related to education.	Howells (2018); Ab Rahman et al. (2019)
Plenty of variety in study modes	Existence of need-specific modes for students, instructors, and other users.	Cardonha et al. (2016); Ciolacu et al. (2018); William Penn School District (2020); <i>Student/Academicians view</i>
Analytics and reporting functionality	The platform analyzes and reports users' access, users' data based on demand such as success statistics.	URL1; Ciolacu et al. (2018); Aristin et al. (2020); <i>Student/Academicians view</i>
Availability	The platform can be used by all users in the education system.	Salavati (2016); Buasuwan (2018); Sharma (2019); <i>Student/Academicians view</i>
Integrating and re-elaborating digital content	Renewing the content applied in physical education for the digital environment and integrating it into the system.	European Commission (2019); Aristin et al. (2020); <i>Student/Academicians view</i>

Table 4.2: Expectations for the digital education platforms (*continue*)

Expectations	Brief explanation	Sources
User-friendliness		
Student attentiveness and concentration	Supporting the classroom environment by the platform to keep student concentration at the maximum level.	Tiven et al. (2018); Buzov (2020); Jamaludin et al. (2020); <i>Student/Academicians view</i>
Self-efficacy of students	Providing tools to increase the student's self-learning by the platform.	Tiven et al. (2018); Waghid (2019); Qin et al. (2020); <i>Student/Academicians view</i>
Learner-content-instructor interaction	Ensuring communication and interaction between all users by the platform.	Ciolacu et al. (2017); Faustmann et al. (2019); <i>Student/Academicians view</i>
Personalized progress control	The student can follow his / her knowledge development through the platform.	Faustmann et al. (2019); Waghid (2019); <i>Student/Academicians view</i>
User approval for ethical rules	All users know that their information is processed in the digital system by ethical rules.	Ciolacu et al. (2017); OECD (2019); Jamaludin et al. (2020); <i>Student/Academicians view</i>

The evaluation model includes many expectations. While evaluating technology, both cost and service quality are important. Especially during the pandemic period, there are continuous improvements on the platforms and continuous support is provided. In this case, the costs of the platforms are also approximately close to each other. For this reason, the cost is not included in the evaluation model. At the same time, the platforms are offered free of charge to students and academics.

4.2.2. Alternatives of Digital Education Platform

In the digital distance education model, it is very important to choose the right platform that can meet the needs. For this, the demands for the platforms should be determined. For the lessons to be carried out with digital distance education, planning should be done by taking into account many variables such as the most appropriate resource and activity, the correct and effective communication style, and the appropriate instructional model that will provide the most efficient information transfer to the student (Korableva et al., 2019; Teng et al., 2023).

There are many platforms that provide digital education in the world. This thesis will be discussed in the four most widely used platforms in the world. These platforms are as follows:

- *Blackboard*: Blackboard is a straightforward, user-friendly, and dependable online collaborative learning platform. Because of the collaboration and conferencing technologies, this new solution provides a degree of contact that makes students feel as if they are in the same room. It provides today's students with the connected and engaged learning experience, support network, and learning community that they expect in the classroom, on campus, or online (URL1).

It creates educational technology ecosystems with the platform to address the individual demands of students. These ecosystems, which enable institutions to achieve better results, are designed to provide greater flexibility and active

participation for educators and to create engaging student experiences (URL2). Thanks to an easy-to-integrate, open, scalable platform, institutions make the educational journey of students seamless. Academic effectiveness is improved using Blackboard's digital learning solutions, student interest is kept awake, and their development continues (URL3). The pros and cons of this platform are as in Table 4.3.

Table 4.3: Pros & Cons for Blackboard (URL1, URL2, URL3)

Pros	Cons
It categorizes users based on several criteria such as ability and department.	Its reporting capabilities are restricted.
It combines with social media platforms and video conferencing applications.	It has a limited number of gamification possibilities.
It has a wide ecosystem of educational tools.	It lacks any security-enhancing features.
It provides new courses that are richer in content with an ultra-course view.	Ultra-experience requires cloud-based SaaS configuration.
It has a mobile application (iOS and Android).	

- Google Classroom:** Google Classroom allows users to quickly teach, but the availability of teaching materials also means that students who are unable to attend courses can be given catch-up work and notes, as well as the same supplementary assignments. Google Classroom makes use of common Google office products such as Google Docs, spreadsheet, and presentation apps, as well as audio and video conferencing. Google Drive is available for online storage. There are other administrative tools available to help professors manage their classrooms (URL4).

Table 4.4: Pros & Cons for Google Classroom (URL4, URL5, URL6)

Pros	Cons
It makes it simple to distribute information and notifications.	Some aspects associated with a standard learning management system are missing.
Simplifies the collecting and assessment of student work	Limited integration options
It incorporates some of Google's most popular productivity tools.	No automated updates
Free to use	No automated quizzes and tests
It allows for collaboration between students in a virtual space that mimics that of the real classroom.	It is connecting to the district's learning management system to make the grade transfer process easy.

Users may share and annotate Google Docs, Sheets, and Slides, use Slides to present their studies, and meet remotely using Google Hangouts. Outside of the traditional educational system, Google Classroom works effectively as a mechanism for sharing information, stimulating online conversation, and providing quizzes. Students and instructors may use the same credentials they use for G Suite for Education to access Google Classroom on any device, including PCs, smartphones, tablets, and Chromebooks, thanks to the platform's flexible design (URL5, URL6). The pros and cons of this platform are as in Table 4.4.

- Microsoft Teams:** Microsoft Teams is a collaboration solution in the Office 365 Suite that enables teams to connect via shared notebooks, chat sessions, resource sharing, virtual meetings. Teachers may create groups or courses that involve any member of your organization by utilizing both Microsoft and non-Microsoft technology, including hundreds of third-party apps, making it an excellent fit for clubs, sports teams, and leadership committees. Learners may use their Class

Notebook to share resources, collaborate on projects, delegate responsibilities, and discuss their progress, while teachers can set assignments and exchange files via SharePoint so that students receive personalized copies (URL7).

Table 4.5: Pros & Cons for Microsoft Teams (URL7, URL8, URL9)

Pros	Cons
• Systematic guidance gets teachers started with enjoyable and useful features for their classrooms.	• Because it combines with other Microsoft programs, beginner users may find it difficult to learn how to utilize them as well.
• Integrative approach	• Challenges regarding permission settings
• Easy group creation	• Unnecessary consumption of storage
• Seamless move to a digital workplace	• Because it is not yet linked to an LMS, teachers must either manually add students or use a third-party app to do so.
• Productivity gains and enriched communication	• It lacks a comprehensive method for anonymous marking, archiving, or verifying for originality.
• Increased transparency	

There is also the option of giving students private comments in their notebooks. There are several assessment options available, including feedback via rubrics, files, links, videos, and text. Students can join Class Teams or form their Teams to collaborate on projects and give duties. They may use the built-in Class Notebooks to take and share notes and collaborate on projects (URL8). Students can have virtual meetings with their peers to converse without having to be in the same physical area. Finally, the chat function allows students to quickly engage with other users, and instructors may monitor, moderate, or silence chat sessions to measure student progress and teach important digital citizenship skills (URL9). The pros and cons of this platform are as in Table 4.5.

- *Zoom*: Zoom is a popular video communication program that offers a simple, effective, dependable, and efficient cloud platform for audio and video conferencing, collaboration, chat, and virtual seminars on mobile devices, PCs, and other comparable devices. In its basic plan, this software essentially provides free 40-minute meeting sessions (URL10).

Table 4.6: Pros & Cons for Zoom (URL10, URL11)

Pros	Cons
• Outlook and Google Calendar compatibility	• This software is not entirely free. Its basic plan has a few features but also many limits.
• Easy for participants to join	• The videos can occasionally be unclear, and the audios might be loud.
• Collaborative whiteboard	• There have been various concerns raised about its internet security and protection.
• Annotate on screen share	• The mobile Zoom app for iOS has poor audio quality.

Teachers will often give the URL to a scheduled Zoom session to students when scheduling Zoom sessions. Students may then quickly join the Zoom lesson without having to sign in using their Zoom account. Teachers can eliminate password security if they want to speed up the administrative procedure for students to participate in the online class. This feature is handy for managing a meeting with more than a hundred attendees (URL11). The pros and cons of this platform are as in Table 4.6.

Platform features, advantages, and disadvantages are constantly updated according to user needs. In this study, DMs evaluate the platforms according to their features in November 2022.

4.3. Application of the Proposed Approach

The education sector is one of the most significant sectors affected by the coronavirus, which caused chaos in the world in a short period. Globally, like in Turkey, the COVID-19 pandemic has had an impact on many nations' education systems, requiring mandated adjustments in how education is delivered, and in this context, countries have moved to digital education rather than traditional face-to-face education.

Due to the coronavirus COVID-19 pandemic, which spread rapidly and caused various crises in the global context, it was stated that schools were closed in 191 countries around the world as of April 17, 2020, and 1,724,657,870 students were affected by this process (UNESCO, 2020). This process has also affected higher education in Turkey as all around the world. Educational activities in 209 universities in Turkey continued by switching from face-to-face courses to online courses as of March 23, 2020. In this context, it has been observed that the factor that greatly affects the quality of education is the effectiveness of the platform used.

In this thesis, expectations for the digital education platforms are determined by taking literature review, industrial reports, academician views, and student views. The digital education platforms that will be evaluated within the scope of these expectations are determined as “Blackboard, Google Classroom, Microsoft Teams, and Zoom”. In this context, expectations are prioritized with the fermatean fuzzy DEMATEL method, and the digital education platforms are evaluated with the fermatean fuzzy MACONT method.

During the evaluation process, the opinions of a total of 12 DMs, including 3 industrial experts, 3 academicians, and 6 students, are taken. All three industrial experts have sufficient knowledge and experience in the field of digital education. The first expert has over ten years of private sector experience and worked on a project of digital transformation of educational procedures. The second expert has digitalization experience and offers certified education programs on digital platforms and institutions. The third expert has also worked in the private sector and is a guest lecturer at

universities. Academics are people who teach in the engineering faculty and work on digital transformation, digitalization, etc. Students are third and fourth-grade students studying at the faculty of engineering during the pandemic process. Experts' evaluations, academics' evaluations and students' evaluations were collected using the Delphi method and these three different evaluations were aggregated.

In this part, firstly, the structure is created. The DMs evaluated the “Technique/Infrastructure” expectations via the linguistic scale presented in Table 3.4. The pairwise matrices obtained from the DMs are combined with the arithmetic mean and fermatean fuzzy operations. These fermatean fuzzy numbers are converted to crisp numbers with (3.4.1) and the direct-relation matrix is formed. Then, the normalized direct-relation matrix is calculated with (3.4.2) and (3.4.3) as in Table 4.7.

Table 4.7: The normalized direct-relation matrix for “Technique/Infrastructure” expectations

	E11	E12	E13	E14	E15
E11	0.000	0.220	0.228	0.220	0.181
E12	0.175	0.000	0.254	0.270	0.300
E13	0.228	0.155	0.000	0.186	0.239
E14	0.155	0.280	0.155	0.000	0.224
E15	0.221	0.221	0.254	0.221	0.000

Then, the total-relation matrix is constructed as in Table 4.8 by using equation (3.4.4) and normalized direct-relation matrix. The threshold value is determined as 1,4390. The values greater than this threshold value are indicated in gray in Table 4.8.

Table 4.8: The total-relation matrix for “Technique/Infrastructure” expectations

	E1	E2	E3	E4	E5
E11	1.139	1.435	1.458	1.459	1.493
E12	1.457	1.440	1.662	1.680	1.770
E13	1.279	1.337	1.219	1.380	1.473
E14	1.251	1.453	1.385	1.257	1.499
E15	1.397	1.518	1.560	1.544	1.427

All these steps are applied for each main expectation. The D, R, D+R, D-R, and D-R values of all expectations are calculated as in Table 4.9 by using (3.4.5) and (3.4.6). Finally, the weights are obtained with (3.4.7)-(3.4.8) as in Table 4.9.

Table 4.9: Final results

Main Expectations	Sub-expectations	D+R	D-R	Category	Weights	Normalized weights
E1	E11	13.507	0.461	CAUSE	0.188	0.0469
	E12	15.192	0.826	CAUSE	0.211	0.0528
	E13	13.972	-0.596	EFFECT	0.194	0.0486
	E14	14.165	-0.475	EFFECT	0.197	0.0492
	E15	15.108	-0.216	EFFECT	0.228	0.0571
E2	E21	9.291	-0.551	EFFECT	0.210	0.0525
	E22	7.868	0.600	CAUSE	0.194	0.0484
	E23	6.543	-0.187	EFFECT	0.161	0.0402
	E24	8.506	-0.158	EFFECT	0.209	0.0522
	E25	8.488	0.296	CAUSE	0.208	0.0521
E3	E31	11.067	-0.539	EFFECT	0.213	0.0532
	E32	10.357	-0.087	EFFECT	0.199	0.0497
	E33	8.857	-0.583	EFFECT	0.170	0.0426
	E34	11.675	0.391	CAUSE	0.224	0.0561
	E35	10.044	0.818	CAUSE	0.194	0.0484
E4	E41	8.655	0.283	CAUSE	0.196	0.0489
	E42	10.281	-0.337	EFFECT	0.232	0.0581
	E43	7.945	0.257	CAUSE	0.179	0.0449
	E44	9.667	-0.329	EFFECT	0.218	0.0546
	E45	7.722	0.126	CAUSE	0.174	0.0436

At the end of the fermatean fuzzy DEMATEL method, sub-expectations' weights are computed. The results indicate that “self-efficacy of student (E42)” is the most appropriate expectation followed by “system security (E15)”. Similarly, “availability (E34)” is obtained as the third-ranked expectation.

In this part, four digital platforms (i.e. Blackboard, Google Classroom, Microsoft Teams, and Zoom) are evaluated with fermatean fuzzy MACONT. In the evaluation process, the names of these platforms are not used for confidentiality reasons. These platforms are named "A1, A2, A3, A4", not respectively.

Firstly, DMs use the linguistic scale in Table 3.6 to assess expectations and platforms. Table 4.10 illustrates an evaluation matrix with the evaluations of DMs. Each of these linguistic expressions corresponds to a fermatean number. These fermatean numbers are then converted into crisp numbers using the equation (3.4.9) and matrix X is formed.

Table 4.10: Evaluation matrix

	E11	E12	E13	E14	E15	E21	E22	E23	E24	E25
A1	H	H	A	A	VH	AL	VL	AH	AH	MH
A2	VH	AH	H	H	H	A	H	ML	ML	H
A3	AH	MH	VH	H	VH	VH	H	AH	VH	AH
A4	VH	MH	MH	AL	MH	MH	VH	L	L	H
	E31	E32	E33	E34	E35	E41	E42	E43	E44	E45
A1	VL	VH	AH	AH	AH	L	AH	VL	AH	A
A2	AL	H	VH	AH	MH	MH	ML	A	AL	L
A3	VH	AH	AL	VH	A	MH	MH	VH	VL	L
A4	H	H	AL	AH	A	VH	ML	MH	AL	L

Then, three different normalization techniques are applied by using (3.4.10)-(3.4.15) to create the normalized decision matrix. These normalized matrices are shown in Table 4.11-4.13.

Table 4.11: Type-1 normalized matrix

	E11	E12	E13	E14	E15	E21	E22	E23	E24	E25
A1	0.213	0.242	0.189	0.225	0.277	0.148	0.140	0.344	0.355	0.216
A2	0.254	0.317	0.261	0.311	0.233	0.218	0.269	0.165	0.170	0.237
A3	0.279	0.221	0.311	0.311	0.277	0.359	0.269	0.344	0.323	0.310
A4	0.254	0.221	0.238	0.153	0.212	0.275	0.321	0.148	0.153	0.237
	E31	E32	E33	E34	E35	E41	E42	E43	E44	E45
A1	0.162	0.265	0.376	0.243	0.357	0.157	0.377	0.155	0.465	0.300
A2	0.154	0.222	0.342	0.243	0.248	0.255	0.180	0.217	0.175	0.233
A3	0.372	0.291	0.141	0.270	0.197	0.255	0.262	0.356	0.185	0.233
A4	0.312	0.222	0.141	0.243	0.197	0.333	0.180	0.272	0.175	0.233

Table 4.12: Type-2 normalized matrix

	E11	E12	E13	E14	E15	E21	E22	E23	E24	E25
A1	0.763	0.763	0.609	0.726	1.000	0.414	0.436	1.000	1.000	0.697
A2	0.910	1.000	0.839	1.000	0.839	0.609	0.839	0.479	0.479	0.763
A3	1.000	0.697	1.000	1.000	1.000	1.000	0.839	1.000	0.910	1.000
A4	0.910	0.697	0.766	0.493	0.766	0.766	1.000	0.430	0.430	0.763
	E31	E32	E33	E34	E35	E41	E42	E43	E44	E45
A1	0.436	0.910	1.000	0.900	1.000	0.473	1.000	0.436	1.000	1.000
A2	0.414	0.763	0.910	0.900	0.697	0.766	0.479	0.609	0.376	0.777
A3	1.000	1.000	0.376	1.000	0.554	0.766	0.697	1.000	0.396	0.777
A4	0.839	0.763	0.376	0.900	0.554	1.000	0.479	0.766	0.376	0.777

Table 4.13: Type-3 normalized matrix

	E11	E12	E13	E14	E15	E21	E22	E23	E24	E25
A1	0.000	0.218	0.000	0.459	1.000	0.000	0.000	1.000	1.000	0.000
A2	0.619	1.000	0.588	1.000	0.311	0.333	0.714	0.085	0.085	0.218
A3	1.000	0.000	1.000	1.000	1.000	1.000	0.714	1.000	0.841	1.000
A4	0.619	0.000	0.402	0.000	0.000	0.601	1.000	0.000	0.000	0.218
	E31	E32	E33	E34	E35	E41	E42	E43	E44	E45
A1	0.038	0.619	1.000	0.000	1.000	0.000	1.000	0.000	1.000	1.000
A2	0.000	0.000	0.855	0.000	0.320	0.556	0.000	0.306	0.000	0.000
A3	1.000	1.000	0.000	1.000	0.000	0.556	0.418	1.000	0.033	0.000
A4	0.725	0.000	0.000	0.000	0.000	1.000	0.000	0.585	0.000	0.000

These normalized matrices are aggregated with (3.4.16) and this aggregated matrix is shown in Table 4.14.

Table 4.14: Aggregated normalized matrix

	E11	E12	E13	E14	E15	E21	E22	E23	E24	E25
A1	-0.243	-0.040	-0.251	-0.086	0.183	-0.289	-0.353	0.282	0.306	-0.167
A2	0.026	0.324	0.046	0.214	-0.115	-0.090	0.062	-0.257	-0.234	-0.066
A3	0.191	-0.142	0.254	0.214	0.183	0.309	0.062	0.282	0.212	0.299
A4	0.026	-0.142	-0.048	-0.341	-0.250	0.070	0.229	-0.307	-0.285	-0.066
	E31	E32	E33	E34	E35	E41	E42	E43	E44	E45
A1	-0.242	0.093	0.332	-0.094	0.359	-0.300	0.370	-0.278	0.473	0.323
A2	-0.265	-0.176	0.242	-0.094	-0.005	0.016	-0.203	-0.098	-0.165	-0.108
A3	0.336	0.259	-0.287	0.282	-0.177	0.016	0.036	0.310	-0.144	-0.108
A4	0.171	-0.176	-0.287	-0.094	-0.177	0.268	-0.203	0.066	-0.165	-0.108

The summation of weighted normalized decision matrix for each alternative (π_i), product of weighted normalized decision matrix (Q_i), two mixed aggregation scores (M_{i1}, M_{i2}), and final aggregated score of each alternative (M_i) are calculated with (3.4.17)-(3.4.20). The alternative with the highest M_i value is identified as the best. The results are indicated in Table 4.15.

Table 4.15: Final results

	π_i	Q_i	M_{i1}	M_{i2}	M_i	Ranking
A1	0.0142	0.6511	0.1663	0.0041	0.4325	2
A2	-0.0478	0.5604	-0.0462	0.0019	0.1377	3
A3	0.1219	2.4752	0.8465	0.0030	0.6787	1
A4	-0.0882	0.5557	-0.1746	-0.0022	-0.2792	4

According to the results in Table 4.15, the most appropriate platform is determined as the “Microsoft Teams”. The other platforms are final ranked as:

$$A3 > A1 > A2 > A4.$$

4.4. Obtained Results and Discussion

For the education system to adapt to the requirements of the information society, its aims must be reorganized to meet the needs of the age. With the rapid developments in technology, the digital education approach that meets the needs of individuals and adapts to today's conditions comes to the fore.

In this context, this thesis proposed an evaluation model that consists of expectations for digital education platforms. In the first part, academic studies in the literature and industrial reports about this subject were examined, and the opinions of experts, students, and academicians were collected. At the end of this part, the proposed evaluation model, which consists of expectations and digital education platforms was determined. While making the evaluations, opinions were taken from 3 experts, 3 academicians, and 6 students.

In the second part, the importance degrees of these expectations were computed with the fermatean fuzzy DEMATEL method. According to the obtained results, the three most appropriate expectations were ranked as “self-efficacy of student (E42)”, “system security (E15)”, “availability (E34)”. These expectations are the points to be considered to increase the effectiveness of education platforms and to achieve efficient results. First of all, in order to be successful, the student must be self-motivated and self-sufficient. It

is very important that the platform is accessible and usable by everyone. Users should be able to access it from any device whenever and wherever they want, and they should be able to watch the course recordings again and again. At the same time, the course materials offered in digital education should be available. In addition, the reliability of the system is also very important for the user.

Looking at the results of the fermatean fuzzy DEMATEL method, it is possible to see the connection between expectations. An impact-diagram map is obtained by plotting points $D+R$ and $D-R$ on a coordinate plane with horizontal axis $D+R$ and vertical axis $D-R$. The horizontal axis shows the importance of the criterion and the vertical axis shows the influence of the criterion. In this direction, graphs are created within the scope of each main expectation and it is shown which sub-expectation affects the other (Figure 4.2).

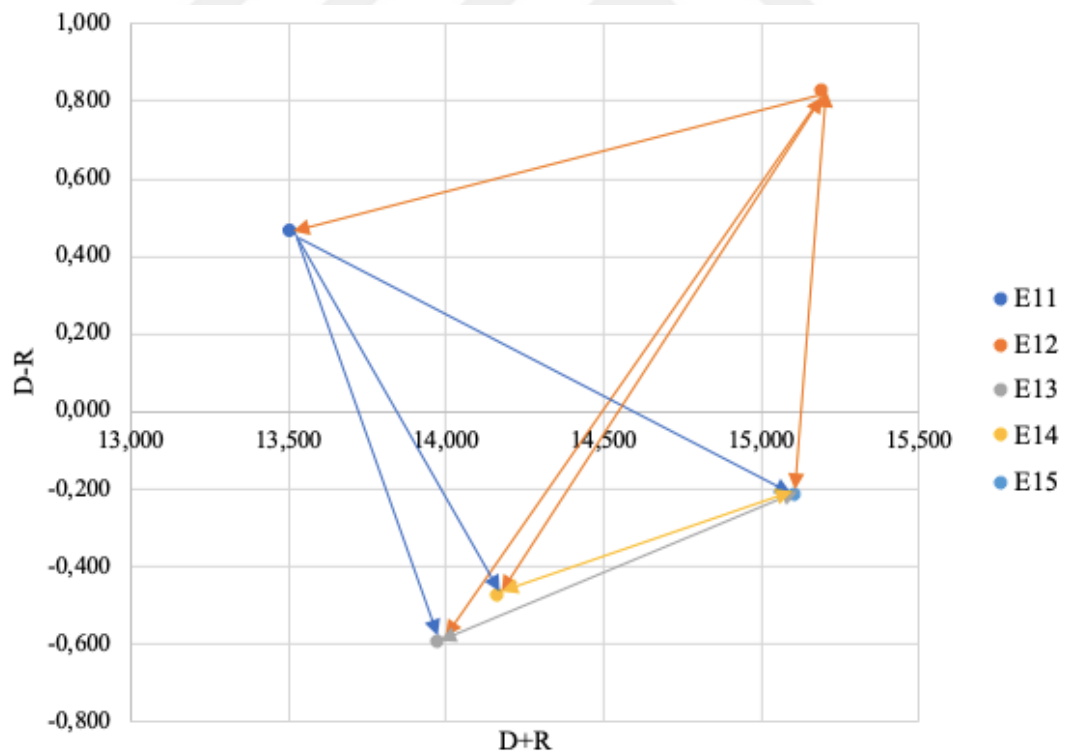
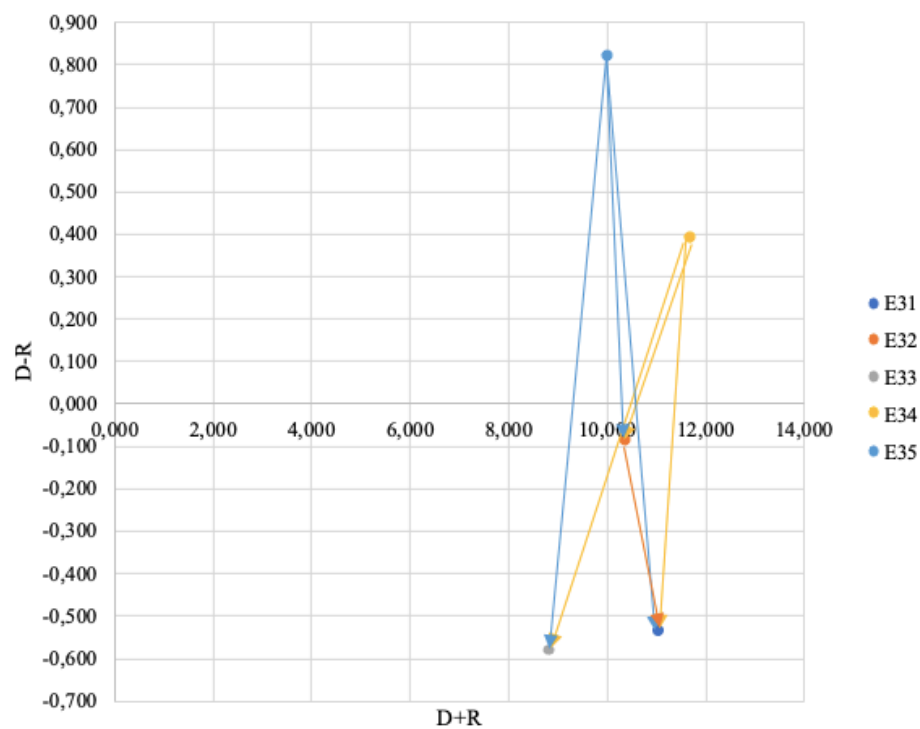
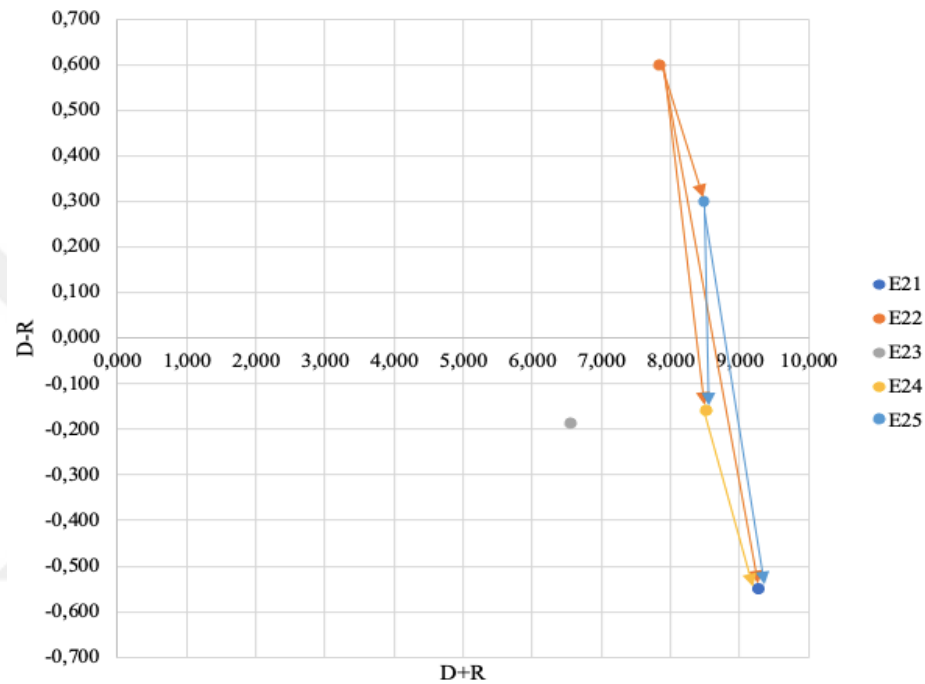


Figure 4.2: Impact-diagram map for “Technique/Infrastructure” expectations

In the first expectation, E12, which is the highest positive value of $D-R$, is considered to have a higher impact and priority over the other expectations. E11 is the other

influencing expectation. E13, which is the highest negative value of D-R, is considered to have a higher impact than the other criteria. This is followed by expectations E14 and E15, respectively. E12, which has the highest value in D+R, is more related to other expectations with a high degree of importance. This is followed by E15, E14, E13, and E11 respectively.



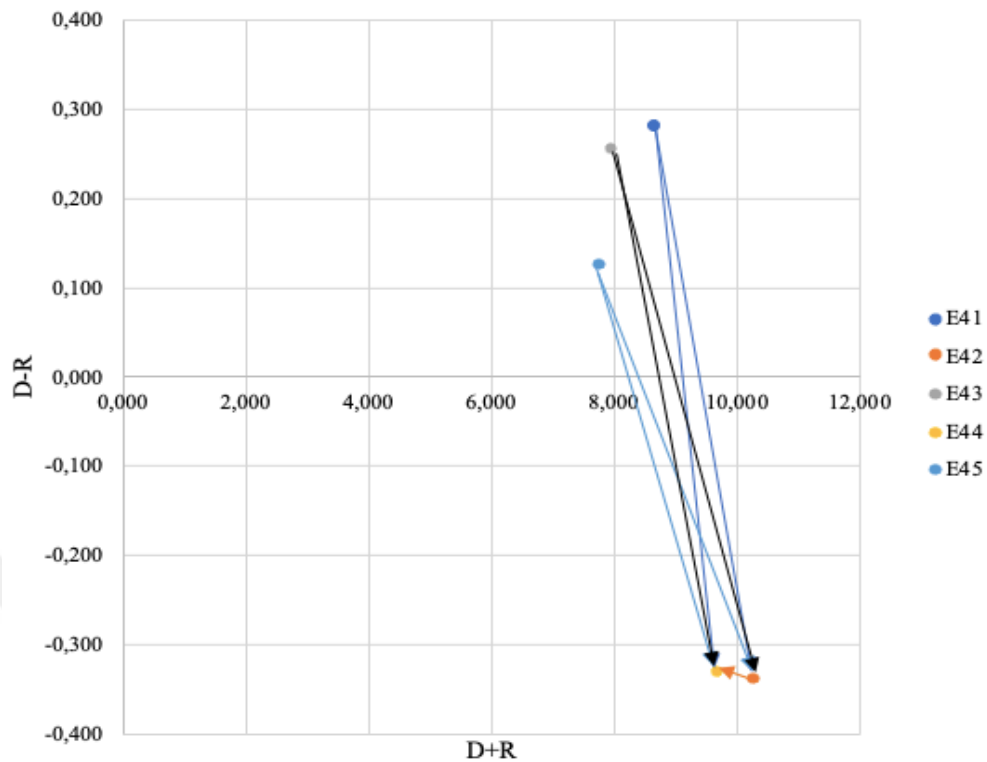


Figure 4.3: Impact-diagraph map for other expectations

According to the findings, there is a substantial inner dependency on "Technique/Infrastructure" expectations. It is also demonstrated by the converging D+R values, which reflect the degree of relationship and demonstrate a significant inner reliance. The other sub-expectations "Digital Competency," "Functionality," and "User-friendliness" are investigated in the same way, and their underlying relationships are computed and presented in Figure 4.3.

In terms of degree of importance, E21 is ranked in first place and E24, E25, E22 and E23, are ranked in the next places. In this study, E22, E25 are considered to be as a causal variable, E21, E23, E24 are regarded as an effect. In terms of relevance, E34 is placed top, with E31, E32, E35, and E33 ranking second through fourth. In this study, E34 and E35 are treated as causative variables, whereas E31, E32, and E33 are viewed as effects. E42 is placed first in terms of significance, with E44, E41, E43, and E45 ranking second through fifth. E41, E43, and E45 are considered causative variables, whereas E42 and E44 are considered effects.

In the last stage, the digital education platforms were evaluated with the fermatean fuzzy MACONT method, and the ranking of the platforms was obtained. At the end of this stage, "Microsoft Teams" was found as the most appropriate platform. Due to confidentiality conditions, the names of other platforms are not disclosed.

In this chapter, digital education platforms are evaluated using the fermatean fuzzy MACONT method, and the expectation weights obtained by the fermatean fuzzy DEMATEL method are used in this evaluation. The same digital education platforms are evaluated with the fermatean fuzzy VIseKriterijumsa Optimizacija I Kompromisno Resenje (VIKOR), fermatean fuzzy Complex Proportional Assessment (COPRAS), and fermatean fuzzy Evaluation based on Distance from Average Solution (EDAS) to test the robustness of the obtained results of the fermatean fuzzy MACONT method. Since the MACONT method uses the normalization technique used in these three different MCDM methods, these methods were selected. Also, the same fermatean fuzzy DEMATEL results are used in this comparative analysis to evaluate the efficacy of the different ranking methods.

VIKOR is a distance-based method for evaluating and ranking options. The VIKOR method is a method developed for multi-criteria optimization of complex systems. This method makes a choice between alternatives in the presence of conflicting criteria and focuses on ranking these alternatives. It is the identification of the "ideal solution" based on "proximity" to several criteria. A consensus ranking is made by comparing them according to their closeness to the ideal alternative. The steps fermatean fuzzy VIKOR (Gül, 2021) are applied and the obtained results are illustrated in Table 4.16.

Table 4.16: Results of fermatean fuzzy VIKOR method

	S_j	Ranking	R_j	Ranking	Q_j	Ranking
A1	0.549	1	0.411	1	0.000	1
A2	0.956	3	0.877	3	0.699	3
A3	0.675	2	0.567	2	0.224	2
A4	1.105	4	1.111	4	1.000	4

COPRAS is a useful method that requires restricted subjective information from the DMs and permits analysis of each qualitative and quantitative criterion (Zavadskas et al., 1994). This method anticipates direct and proportionate dependency on the importance and utility level of examined alternatives on a system, as well as the weights of the criteria. It may be used to assess complicated criteria and issues with several options, as well as for each of the maximum and lowest criterion values in a multi-criteria evaluation. The steps of fermatean fuzzy COPRAS (Kamali Saraji et al., 2021) are applied and the obtained results are illustrated in Table 4.17.

Table 4.17: Results of fermatean fuzzy COPRAS method

Platforms	Si-	Si+	Qi	Pi	Ranking
A1	0.022	6.024	6.802	100.00	1
A2	0.130	3.750	3.884	57.11	3
A3	0.530	5.571	5.604	82.39	2
A4	0.318	3.655	3.710	54.54	4

EDAS is a distance-based method developed by Ghorabae et al. (2015). It pursues the average solution for comparing alternatives. It is relatively new in the MCDM domain and is particularly useful when the preferred average value of attribute evaluations is known. The steps of fermatean fuzzy EDAS (Mishra et al., 2022) are applied, and the obtained results are illustrated in Table 4.18.

Table 4.18: Results of fermatean fuzzy EDAS method

Platforms	NSP	NSN	AS	Ranking
A1	1.000	0.163	0.582	1
A2	0.172	0.000	0.086	4
A3	0.533	0.355	0.444	2
A4	0.345	0.038	0.191	3

In this study, the fermatean fuzzy MACONT method is deployed for ranking digital education platforms. In addition, fermatean fuzzy VIKOR, fermatean fuzzy COPRAS and fermatean fuzzy EDAS methods are applied to find out the rankings' consistency

and compare the obtained results from fermatean fuzzy MACONT. Table 4.19 shows the ranking of alternatives using these methods.

Table 4.19: Ranking of the platforms with fermatean fuzzy MCDM methods

	fermaten fuzzy MACONT	fermaten fuzzy VIKOR	fermaten fuzzy COPRAS	fermaten fuzzy EDAS
A1	2	1	1	1
A2	3	3	3	4
A3	1	2	2	2
A4	4	4	4	3

As can be seen in Table 4.19, different rankings are obtained with different MCDM methods. The third and fourth-ranked alternatives are the same in the fermatean fuzzy MACONT, fermatean fuzzy VIKOR, and fermatean fuzzy COPRAS methods; however, they are ordered differently in the fermatean fuzzy EDAS method. All of these methods are distance-based and take a common approach. However, as opposed to other methods, the MACONT method is comparatively modern and practical. When compared to the results of other well-known MCDM methods, this integrated fermatean fuzzy MACONT approach yields very stable end values, proving the suggested method's potential to address relevant MCDM problems. In addition, unlike other methods, the MACONT method uses three different normalization techniques. This is one of the strengths that distinguish the method from other MCDM methods.

This integrated evaluation methodology can assist researchers in assessing the potential of digital education platforms and making more informed judgments. This thesis may be used by stakeholders in digital education as a decision support system tool for making early decisions during the development of digital education platforms.

5. PROPOSED NEW METAVERSE-BASED EDUCATION SYSTEM WITH QFD APPROACH

This chapter of the thesis proposes a new metaverse-based education system with QFD approach. The proposed approach consists of an QFD-based design model and the validation of the proposed model using integrated fermatean fuzzy AHP-based QFD approach. This chapter contains four main sections as follows: literature review of metaverse-based education, proposed QFD-based model, application of the proposed approach, and obtained results. Details concerning these sections are presented below.

5.1. Literature Review of Metaverse-based Education

5.1.1. Metaverse in Education

Metaverse was first used in 1992 in a science fiction novel titled *Snow Crash* (Stephenson, 1992). After Cline's (2011) book *Ready Player One* moved to the film world in 2018, the subject of Metaverse has become more concrete and interesting for people. Metaverse's best-known virtual environments are Second Life, Zepeto, Roblox, Minecraft, Gather Town, and Fortnite. These platforms provide a virtual world-oriented user experience through their advanced 3D graphics (Park & Kim, 2022a; Rospigliosi, 2022a).

One of the first successful examples of the Metaverse universe is the Second Life platform created by Linden Labs in 2003 (Suh & Ahn, 2022). People communicate through avatars on the Second Life platform and bring their daily lives to the virtual. Stephenson (1992) described avatars in his book as audio-visual bodies that individuals use to connect with one another in the Metaverse environment. In 3D-based Metaverse

environments, users can thus meet each other, buy and sell various digital assets, and form a community/group.

In the last twenty years, Metaverse tools have started to enter our lives predominantly. Metaverse has become one of the most popular topics of recent years, with the adoption of high-quality computers and high-speed internet network, and the spread of 5G. (Lee et al., 2022; Wu & Hao, 2023).

Metaverse world on the axis of “Augmentation versus Simulation” and “Intimate versus External” are discussed by Smart et al. (2007) in their report titled Metaverse Roadmap led by the Acceleration Studies Foundation. These axes offer four dimensions with overlapping technologies: Virtual Worlds, Mirror Worlds, Lifelogging, and Augmented Reality. In order to understand these four categories shown in Figure 5.1 and the relationships between them, it is important to first examine the axes.

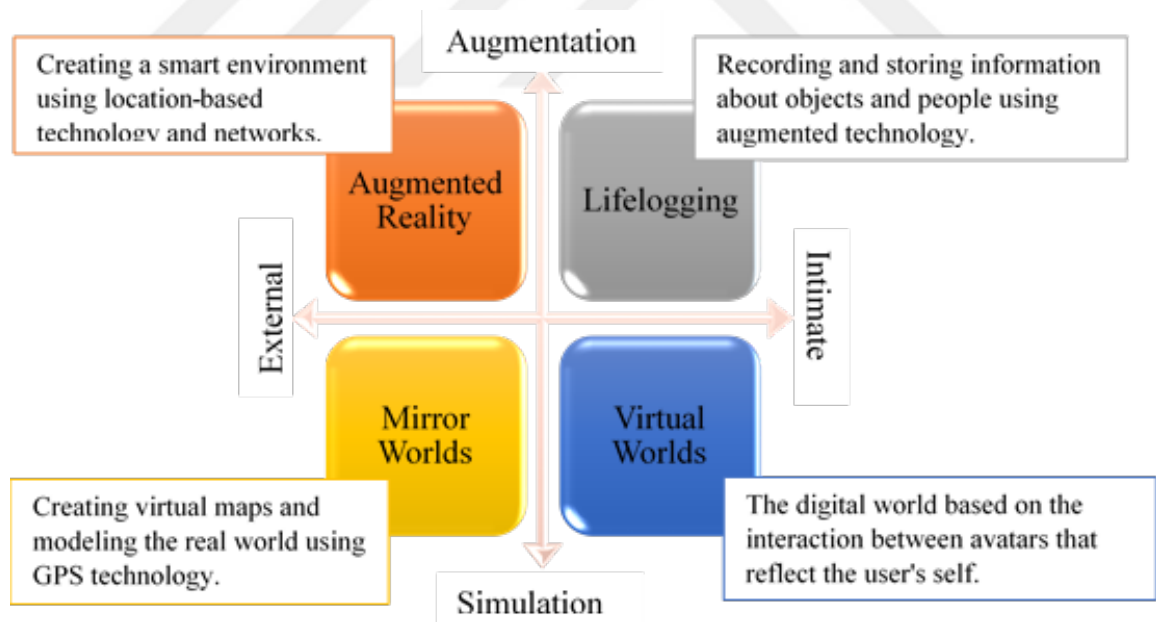


Figure 5.1: Diagram of four types of the Metaverse (Smart et al., 2007)

One of the areas where Metaverse has made significant transformations is academic and professional education. In fact, this change started with virtual reality and augmented reality, which are the main technological components of Metaverse. With the pandemic, technology companies have started to offer more digital education solutions such as

Metaverse School. A university in South Korea has started to provide a “virtual campus” service to university students around the world, a kind of metaverse (PSU, 2018).

One of the key components of Metaverse is augmented reality, which gives on-site, real-time, step-by-step visual instruction on operations such as machine operation, product assembly, and warehouse management. Metaverse also plays an essential role in defense training and exercises. The US Air Force conducts studies to carry out training and activities with "the most realistic simulations" in pilot training. The UK Ministry of Defense supports Metaverse research to make drills and simulated training more realistic and reduce costs (Jung et al., 2022). It is expected that all armies around the world will show more interest in Metaverse to provide this unique simulator environment in the near future.

Metaversities are campuses created in the Metaverse and represent the next evolution beyond the immersive learning opportunities currently available for students at many colleges and universities. Immersive learning experiences in higher education through virtual reality, augmented reality, and augmented reality are becoming increasingly popular as virtual reality tools become available at relatively affordable prices. This has allowed more people to experience virtual reality at home and students to feel more comfortable with vehicles when they encounter vehicles at university. Metaversity consolidates such encounters into a single unified area. Students collaborate as avatars in a metaversity setting. Avatars can study in the library or go out to the courtyard to interact with other classmates on a "digital twin" campus (Viano, 2023).

Metaverse's learning opportunities that go beyond the limits of Internet technology go beyond the benefits of e-learning. In the new era in which remote working transforms the way of doing business, Metaverse is expected to offer faster and more effective development opportunities. While providing all these, metaverse-based education should have some features. These features can be listed as follows:

- *Openness for educational users:* Metaverse-based training should be available to all training users. All users can be on the Metaverse simultaneously, individually or with agents. Metaverse makes everyone feel like an "entity". Anyone can be a part of the Metaverse and attend a class (Mustafa, 2022; Pimentel et al., 2022).
- *Synchronous game-based learning:* Gaming is possibly the most common application of augmented reality. Games that adjust difficulty based on need and competency can engage learners by giving a scaffolded chance for repeated practice (Pimentel et al., 2022; Chen, 2022; Lin et al., 2022).
- *Immersive interactive experience:* Metaverse-based education removes the limitations of web-based teaching in Web 2.0. It provides instructors and students with an immersive experience, enabling them to enjoy a teaching classroom more and learn more effectively in a realistic experience environment (Pimentel et al., 2022; Zhang et al., 2022; Lin et al., 2022; Zhou, 2022).
- *Unrestricted time and space:* It is independent of the time and place limitations of metaverse-based education. Historical events can be recreated and lived. When students from temperate regions desire to experience the environment of the tropics near the equator, they can use the Metaverse if digital models of the tropics have been used. Thus, geographical restrictions are also removed (Zhang et al., 2022; Lin et al., 2022; Büyüközkan, 2022).
- *Role-play and perspective-taking in 3D learning scenes:* In metaverse-based education, a variety of realistic learning scenes can be simulated and created using technologies such as digital twins, augmented reality, virtual reality, extended reality etc. Virtual reality can potentially induce feelings of virtual body ownership or presence in a separate body. This can help people gain social and emotional skills or improve their self-beliefs by facilitating role-playing and perspective-taking, which are powerful educational tools for identity development (Pimentel et al., 2022; Chen, 2022).
- *Digital instructor/learner identity:* It is their own 3D identity that teachers and students have in the Metaverse world. Users can customize and build their own panoramic and 3D environments. Students can change their outfits and haircuts at any time, as human-looking passport photos can be taken, modified and updated (Zhang et al., 2022; Jovanović & Milosavljević, 2022; Chen, 2022).

- *Hardware independence:* The main purpose of this characteristic is to make education support accessible to all users. Metaverse-based education can be used by many different hardware. The use of tools that offer different sensory environments and experiences and the ability to work with different tools makes this training concept more demanding. This provides real-time and environment-independent metaverse-based education accessibility on mobile (Mustafa, 2022; Zhou, 2022).
- *Decentralized and editable educational content:* Metaverse-based education allows users to take part in various activities (e.g. learning, education, work, socializing) and interact with other users and virtual objects through avatars and provides users with opportunities to edit their educational content. Users may also have more immersive, embodied, and richer experiences than ever before (Zhang et al., 2022; Lin et al., 2022).
- *Personal learning network:* In metaverse-based education, the personal learning tool automatically collects information about the user's learning goal and sends a report to them on a regular basis. Thus, progress in learning is tracked simultaneously (Lin et al., 2022; Zhou, 2022).
- *Interactive communication and collaboration:* Teachers can have internal meetings in virtual rooms created using metaverse-based education. Simultaneously, students may set up study areas in which they can collaborate, learn, and interact freely. Everyone can see each other, effortlessly trade data, and play games based on their avatar. These qualities enhance student-teacher connections, communication, and cooperation (Jovanović & Milosavljević, 2022; Zhang et al., 2022; Pimentel et al., 2022; Chen, 2022).
- *Convergence of the virtual and real educational world:* Metaverse-based education is a combination of a virtually developed real education world and a physically permanent virtual education world. The gap between the virtual and physical worlds is bridged in metaverse-based education, making the Metaverse experience more immersive, multi-sensory, and realistic (Zhang et al., 2022; Zhou, 2022).

Metaverse-based education enables students to learn better and faster through virtual, collaborative, and task-oriented learning. It provides as much variety and interaction as a real-world classroom. In this way, every student is supported with hands-on learning opportunities (Reyes, 2020; Ortega-Rodríguez, 2022). Teachers act as facilitators, observers, and guides in the Metaverse. Understanding the particular strengths and limitations of the students, a teacher can choose or construct lesson plans that appeal to each child's learning style (Park, 2021; Ortega-Rodríguez, 2022).

Metaverse allows students to gain experience and practice without limits. Thus, it settles in their memory and makes learning more effective. Technologies used in the Metaverse environment also help teachers and save time. Some other benefits of Metaverse environments are as follows (Reyes, 2020; Siyaev & Jo, 2021; Lee & Hwang, 2022; Ge, 2022; Inceoglu & Ciloglulil, 2022; Lee et al., 2022):

- Creating engaging and lifelike learning spaces
- Encouraging communication
- Providing personalized learning opportunities
- Making learning fun and engaging
- Supporting immersive learning
- Promoting interdisciplinary learning
- Encouraging cross-collaboration and teamwork
- Enriching gamification
- Increasing co-operation
- Providing a transparent and flexible learning environment

5.1.2. Data Collection

This literature review is handled in two branches as the analysis of academic literature review and industrial reports on the metaverse-based education concept.

The systematic review focused on the concept of Metaverse and education. The standards for Preferred Reporting Items for Systematic Reviews and Meta-Analysis

(PRISMA) (Moher et al., 2009) were followed in the production of this study. Web of Science (WoS), Scopus and Science Direct databases were used while scanning. The databases were searched with the following keywords:

- “metaverse” and “education”
- “metaverse” and “learning”
- “meta-education”
- “metaverse-powered distance education”
- “metaverse-based education”

For the WoS database, the search was done with the specified keywords as Topic (with field tag “TS”). For the ScienceDirect database, the search was done with the specified keywords. For the Scopus database, the search was done with the specified keywords as “TITLE-ABS-KEY” and the search was refined to show only articles.

To discover highly relevant publications answering research topics, criteria for article inclusion and exclusion were developed. This research has been limited to English language journal publications on the topic of the identified keywords, with all studies being related to the concept of Metaverse and education. All articles collected at the stages of the selection process were filtered according to these criteria. The inclusion and exclusion criteria are summarized in Table 5.1.

Table 5.1: Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Relevant to search and published from 2007 until 2022	Outside period of coverage
Listed in the preferred databases	Non-English
Full-text articles	Unavailable full text
Paper written in English	Duplicated studies
	Non-article

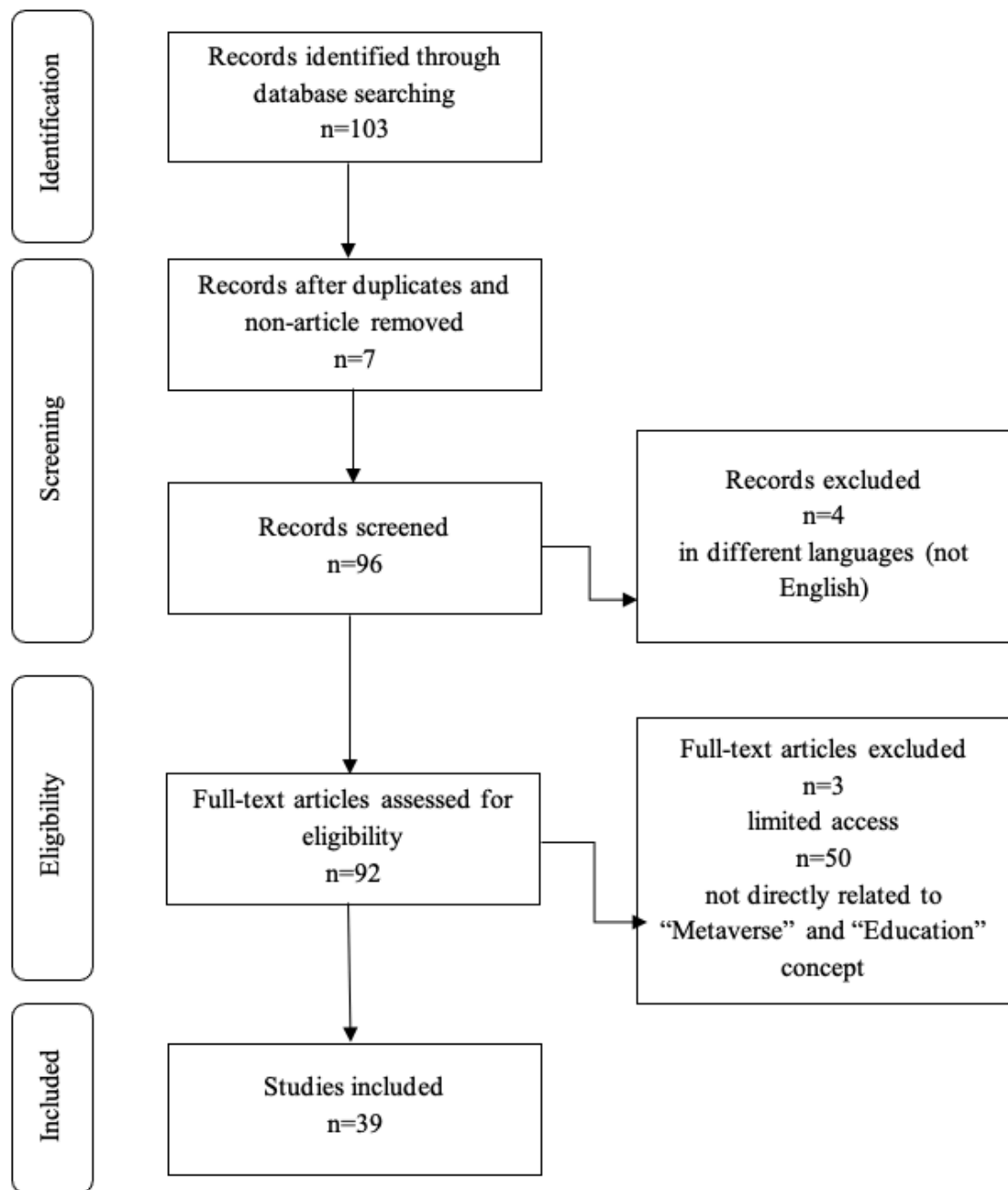


Figure 5.2: A diagrammatic representation of the PRISMA review process with “Metaverse and Education” keywords

The study selection process made within the scope of the determined inclusion and exclusion criteria is as in Figure 5.2. The WoS database searches resulted in 103 records with “Metaverse” and “Education” keywords, of which 7 are duplicates and non-article, 96 articles remained. After the English language selection, 92 studies remained, and abstracts are screened for eligibility. At this stage, 3 studies are excluded because of

limited access and 50 studies are found to be insufficiently related to "Metaverse" and "Education". Finally, 39 studies are included in the final review.

Secondly, the WoS database is searched with the keywords "Metaverse and learning", and 132 studies are accessed. However, since there is a conflict with words such as machine learning and deep learning etc., 85 articles are excluded from the field and 37 articles are reached. Since 33 of these articles are common with the previous search, 4 articles as a result of the screening processes shown in Figure 5.3 are examined. Lastly, 10 different studies are found by searching with the keywords specified in other databases.

In the second part of the literature review, industrial reports are examined. During this review, consulting companies such as Accenture, Gartner, Boston Consulting Group, EY, KPMG, PwC, Deloitte, McKinsey etc. and the keywords "Metaverse + education/learning" are cross-searched. In addition, the following keywords are searched without consulting companies:

- metaverse and education
- metaverse and learning
- metaverse for digital education
- metaverse for online education
- metaverse for online learning
- metaverse for digital learning

Details of these studies will be given in the next sections.

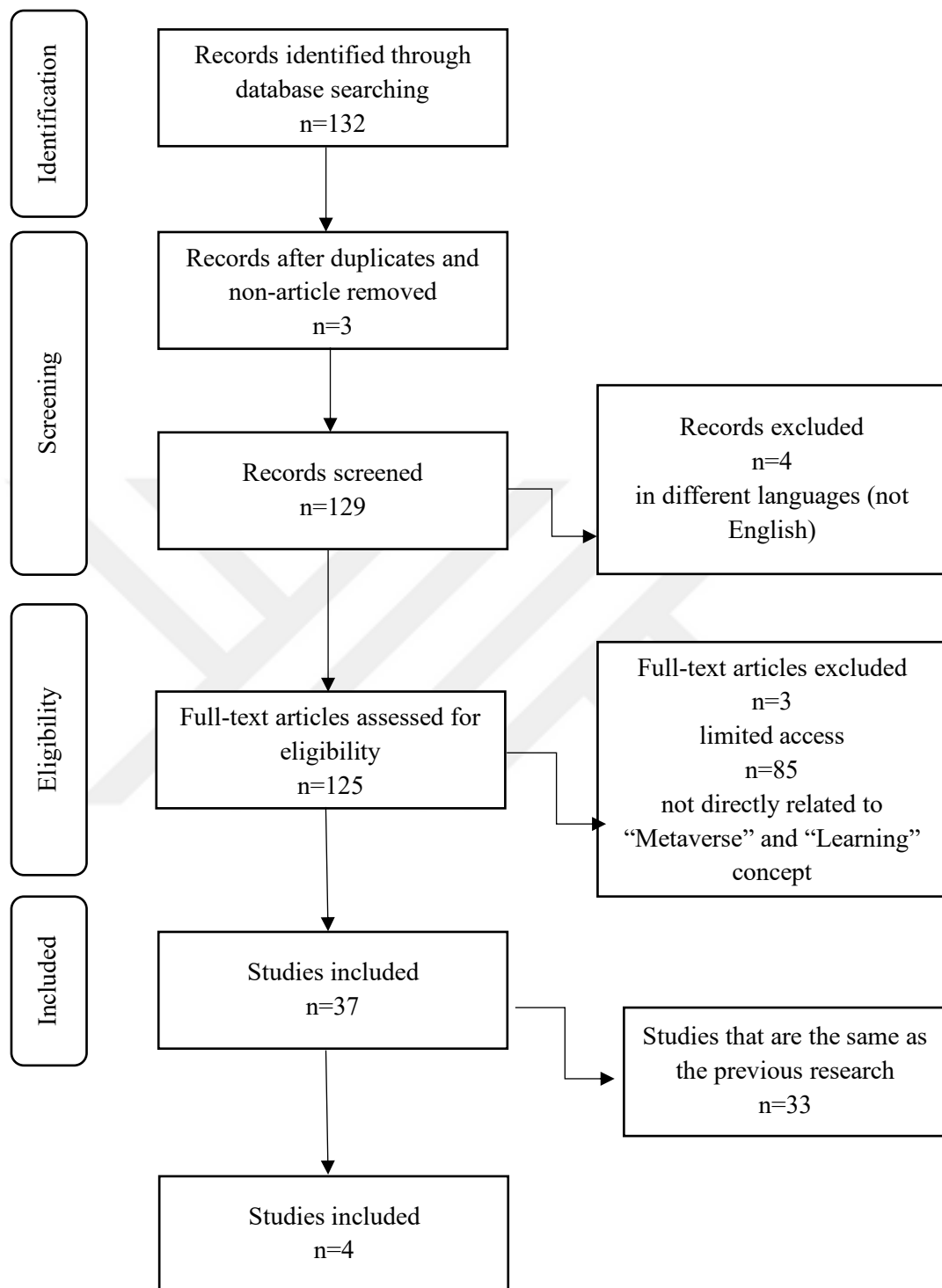


Figure 5.3: A diagrammatic representation of the PRISMA review process with “Metaverse and Learning” keywords

5.1.3. Data Analysis

5.1.3.1. Academic Literature on Metaverse-based Education

In this section, after the selection process, 53 studies presented between 2008 and 2022 are examined. Among these studies, the research articles are listed in Table 5.2, and the review articles are listed in Table 5.3.



Table 5.2: Research papers concerning metaverse-based education

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2008	Ayiter	To present the learning content of the creative fields in the open-ended three-dimensional structure of a Metaverse	Art Education	-	Humanities	-
2010	Kanematsu et al.	To present multilingual discussion environment in Metaverse	Language Education	-	Computer Science	VR
2010	Rapanotti & Hall	To focus on the lessons learnt from the viewpoint of managing the development of the learning environment	Higher Education	-	Education & Educational Research	VR, AR
2012	Clark	To present virtual laboratory environment	Immersive Education	-	Education & Educational Research	-
2012	Schaf et al.	To develop prototype for learning environments	Engineering Education	-	Computer Science	VR, MR, 3D
2012	Nishino et al.	To investigate how the three e-learning modes affect the learners' learning preferences	General Education	-	Computer Science	ICT

Table 5.2: Research papers concerning metaverse-based education (*continue*)

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2013	Wagner et al.	To propose a Metaverse that provides students with vocational courses given through programs, as well as assistance through remote education technology	Distance Education	-	Computer Science	3D, VR
2013	Bilhao Gomes & Klein	To determine if and how the usage of Metaverse technology may aid in the development of collaborative skills in remote education	Distance Education	-	Computer Science	3D, VR
2014	Kanematsu et al.	To present an application for a virtual class for nuclear safety education	Nuclear Safety Education	-	Computer Science	3D, VR
2014	Masferrer et al.	To share teaching experiences using Metaverse remote seminars and videos	Distance Education	-	Computer Science	VR
2014	Pena Arcila	To build the system integrating a learning management system	Virtual Education	-	Education & Educational Research	3D, VR

Table 5.2: Research papers concerning metaverse-based education (*continue*)

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2015	Schlemmer & Backes	To share some research-related experiences in the framework of the Digital Education Research Group	-	-	Psychology	VR
2015	Barry et al.	To evaluate students' learning manner	Secondary Education	-	Computer Science	VR
2017	Jaramillo-Mujica et al.	To define the processes of scenario development, conception, and execution in the OpenSim platform	Physics Mechanics Education	Statistical Methods	Engineering	3D, VR
2019	MacCallum & Parsons	To found that experienced teachers tended to concentrate on content	Teacher Education	Statistical Methods	Computer Science	AR
2019	Alvaro-Farfan et al.	To study the usage of virtual worlds as an evaluation tool for students	Secondary Education	-	Computer Science	VR
2020	Díaz	To demonstrate the potential of a virtual environment as an academic resource that stimulates both students and teachers to build new digital skills and competences	General Education	-	Education & Educational Research	VR

Table 5.2: Research papers concerning metaverse-based education (*continue*)

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2020	Díaz et al.	To solve the challenge of designing, developing, and implementing a virtual or Metaverse world in an educational setting using Scrum methodology	General Education	-	Education & Educational Research	VR
2020	Reyes	To characterize high school students' attitudes toward Metaverse	General Education	Statistical Methods	Education & Educational Research	AR
2021	Siyaev & Jo	To present mixed reality education and training for Boeing 737 airplane maintenance with smart glasses	Aircraft Maintenance Education	Convolutional Neural Networks	Computer Science	3D, AI, AR, VR, MR, ER
2021	Park	To investigate cases of Metaverse technology being used in Korean language instruction	Language Education	-	Language & Linguistics	-
2021	Park et al.	To investigate the variations in learning motivation among various player types	Gamification	Statistical Methods	Science & Technology	HCI

Table 5.2: Research papers concerning metaverse-based education (*continue*)

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2021	Siyaev & Jo	To propose the use of the Metaverse for Boeing-737 airplane maintenance training and instruction	Aircraft Maintenance Education	Speech Recognition Algorithms	Computer Science	3D, DL, AI, AR, VR, MR, ER
2021	Lopes & Gonçalves	To understand whether augmented reality technologies can contribute to inform and educate children in primary school	Primary Education	-	Computer Science	AR
2022	Almarzouqi et al.	To assess students' perceptions of Metaverse application in the United Arab Emirates	Medical Education	Statistical Methods	Computer Science	VR, 3D, ML
2022	Lee et al.	To adapt Heart Sutra's fuzzy ontology principles to artificial intelligence	Language Education	Fuzzy Markup Language	Computer Science	AI
2022	Hedrick et al.	To comprehend the significance of facilitating a virtual classroom	Metaverse Classroom Exploration	-	Computer Science	VR
2022	Huh	To demonstrate the advent of the Metaverse in medical education through the use of computer-based assessment	Medical Education	Computer-based Testing	Education & Educational Research	VR, AR

Table 5.2: Research papers concerning metaverse-based education (*continue*)

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2022	Jovanović & Milosavljević	To enable participants to identify the primary benefits of online instruction utilizing the VoRtex platform	Gamification	Statistical Methods	Computer Science	VR
2022	Li et al.	To provide techniques for increasing football instruction quality in a mobile Internet environment	Football Education	Simulation	Computer Science	AI, VR
2022	Dahan et al.	To investigate various past studies in order to determine which particular technologies should be given by the Metaverse framework	General Education	-	Computer Science	DT, CC, 3D, VR, AR, ER, NI, BC
2022	Lee & Hwang	To introduce ground-breaking ideas into the fundamental area of sustainable education research	-	-	Science & Technology	VR, AR, 3D
2022	Guo & Gao	To develop an immersive situational English-teaching scenario in order to identify students' emotion electroencephalograms	English-Teaching Education	Convolutional Neural Networks –Recurrent Neural Networks Fusion Models	Psychology	VR, AR, NI, 5G

Table 5.2: Research papers concerning metaverse-based education (*continue*)

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2022	Suh & Ahn	To investigate the Metaverse's experiences and attitudes toward learner-centered education	Learner-Centered Constructivist Education	Statistical Methods	Psychology	VR, AR
2022	Lee et al.	To propose a system that blends virtual reality and Metaverse approaches into the classroom to address the inadequacies of current remote education models	Aircraft Maintenance Education	Simulation - Statistical Methods	Engineering	VR, AR
2022	Park & Kim	To detect planet kinds in the Metaverse in order to provide players with a fun gaming experience	Gamification	-	Science & Technology	VR, AR
2022	Ge	To define multiple influences of intelligent technologies on students' behaviors	College Education	-	Public, Environmental & Occupational Health	VR, IoT
2022	Zhou	To build a smart education ecosystem	Smart Education	AHP	Computer Science	5G, 3D, CC, VR

Table 5.2: Research papers concerning metaverse-based education (*continue*)

Year	Authors	Aim of the study	Application area	Analytic methods	WoS category	Used technologies
2022	Lo et al.	To propose an 3D virtual reality architecture in the Metaverse	Environmental Conservation Education	Statistical Methods	Engineering	VR, 3D, AR
2022	Chen	To investigate how the Metaverse platform may be used in the field of online education	-	-	Education & Educational Research	VR, 3D, EC
2022	Iwanaga et al.	To better comprehend people who are familiar with Metaverse and its application in anatomy teaching	Anatomy Education	Statistical Methods	Science & Technology	VR, AR, MR
2022	Sun	To address book layout design and investigate how books are built at colleges and institutions	General Education	Text Image Preprocessing Algorithm	Public, Environmental & Occupational Health	-
2022	Sandrone	To present new approach in medical education	Medical Education	-	Biochemistry & Molecular Biology	VR, AR, MR, BC, WT

Table 5.3: Review papers concerning metaverse-based education

Year	Author	Aim of the study	Application area	WoS category	Used technologies
2015	Schlemmer & Backes	To provide the Metaverse's perspective on online education	-	Education & Educational Research	VR, 3D
2021	Kye et al.	To identify the four categories of Metaverse and discuss the possibilities and limitations of their educational uses	Educational Applications	Education & Educational Research	VR, AR, 3D
2022	Zhang et al.	To introduce the visions of the Metaverse in education	-	Psychology	VR, AR, ER, EC, CC, 5G, AI, 3D, IoT, WT
2022	Yu	To increase the scope and depth of further study by providing fundamental statistics indicating the direction of metaverse-based physical education	Physical Education	Engineering	VR, 3D, AR, WT
2022	Tlili et al.	To perform a systematic review of the Metaverse in education literature	-	Education & Educational Research	AI, VR, AR, ER, DT, 3D
2022	Ortega-Rodríguez	To define the Metaverse and its uses in education	-	Education & Educational Research	VR, AR, ER
2022	Stanoevska-Slabeva	To present the concept of Metaverse for education	-	Education & Educational Research	VR, AR, ER, MR

Table 5.3: Review papers concerning metaverse-based education (*continue*)

Year	Author	Aim of the study	Application area	WoS category	Used technologies
2022	Inceoglu & Ciloglulil	To underline how the Metaverse environment may expand the field of educational technology	-	Education & Educational Research	VR, AR
2022	Mustafa	To investigate the attitudes and educational needs of metaverse-based education	-	Education & Educational Research	VR, AR
2022	Hwang & Chien	To give a precise definition of the Metaverse	-	Computer Science	VR, AR, AI

Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), Extended Reality (ER), Artificial Intelligence (AI), Blockchain (BC), Internet of Things/Robotics (IoT/Rob), 5G Technology (5G), Cloud Computing (CC), Edge Computing (EC), 3D Technology (3D), Digital Twin (DT), Wearable Technology (WT), Neural Interfaces (NI), Information and Communication Technologies (ICT), Human-Computer Interface (HCI), Deep Learning (DL), Quantum Computing (QC)

5.1.3.2. Industrial Reports on Metaverse-based Education

Although the reports published by consulting and technology companies on Metaverse have increased in recent years, there are very few industrial reports within the scope of Metaverse in education. These reports are listed in Table 5.4.

Table 5.4: Industrial reports concerning metaverse-based education

Company/ Institution (Year)	Aim of the study	Used technologies
EY-Parthenon (2020)	To demonstrate that institutions and students are in agreement about the influence of digital in this new era of higher education	VR, AR, WT
EY (2022)	To present what needs to be done in the education sector in the 2030 plan	VR, AR, AI
Accenture (2022)	To explain the place of Metaverse in the university of tomorrow	VR, AR, ER, AI, ML, QC, IoT, 5G, EC, CC
JP Morgan (2022)	To design and deploy new emerging technologies to modernize infrastructure and business models in education, such as tokenization and digital identification	VR, AR, 3D
Deloitte (2022)	To explain Metaverse era and the used technologies in this era	VR, AR, ER, BC, AI, IoT, 5G, EC, CC, HCI, DT, 3D
The Brookings Institution (Hirsh- Pasek et al., 2022)	To offer a path for bringing best educational practices into the Metaverse	VR, AR, 3D, ER

Table 5.4: Industrial reports concerning metaverse-based education (*continue*)

Company/ Institution (Year)	Aim of the study	Used technologies
Meridian Treehouse (Pimentel et al., 2022)	To teach the notion of learning in the Metaverse, as well as technology, tools, and four reflective stages, in order to properly reflect on the role that XR may play in your learning practice	VR, AR, ER, 3D, BC, AI, 5G, EC, MR, DT, NI
Thinktech (2022)	To explain the Metaverse concept, its opportunities, threats, and its application areas	VR, AR, 3D, ER, AI, BC, NI, IoT, WT, 5G

Accenture's (2022) "Meet in Metaverse" report presents the changes that can occur with higher education and the journey students can experience with the Metaverse. EY (2020, 2022) reports mention the future of universities. It explains how digital technologies affect universities and students' success with digital tools. Web 2.0 versus Web 3.0 approach to the Metaverse is presented in JP Morgan report (2022). In the Deloitte report (2022), the Metaverse concept and application of Metaverse in healthcare education are presented. Hirsh-Pasek et al. (2022) describes the educational world facing the Metaverse, the challenges faced, and new principles in the Brookings Institution report. Learning in Metaverse concept, technologies, tools, and four reflective levels are presented to effectively reflect on the role XR could play in your learning practice by Pimentel et al. (2022) in Meridian Treehouse report. In the Thinktech report (2022), the concept of Metaverse is defined and explained, and then its application areas are mentioned.

Many technologies supporting Metaverse are presented in industrial reports and academic studies. Analyzing these technologies and determining how much importance should be given to which technology is one of the important elements that make the system successful. According to industrial reports, the most used technologies are seen as "Virtual Reality", "Augmented Reality", "Extended Reality", and "3D Technology".

Our review of metaverse-based education literature signifies a gap in critical success and risk factors in metaverse-based education. Currently, there are relatively several articles and industrial reports on Metaverse and education, but these studies focus on different areas and handle the subject either as conceptual notes or with computer-based algorithms. As far as we know, there are no academic studies that emphasize what should be considered when constructing a Metaverse-based education system, explain what will lead the system to success, and includes the characteristics, roadmaps, success and risk factors of the Metaverse-based education.

5.1.4. Review Results

As a result of the search, 53 studies were obtained and the details of these studies are given in Table 5.2 and Table 5.3. Figure 5.4 shows that almost the same number of studies have been conducted on this subject since 2008. In 2021, there is an increase in the number of articles. In 2022, it can be easily said that there are more publications compared to other years. In this case, it can be said that the COVID-19 pandemic, which started in 2020, also had an effect. In addition, it is seen that review articles have mostly been carried out in recent years.

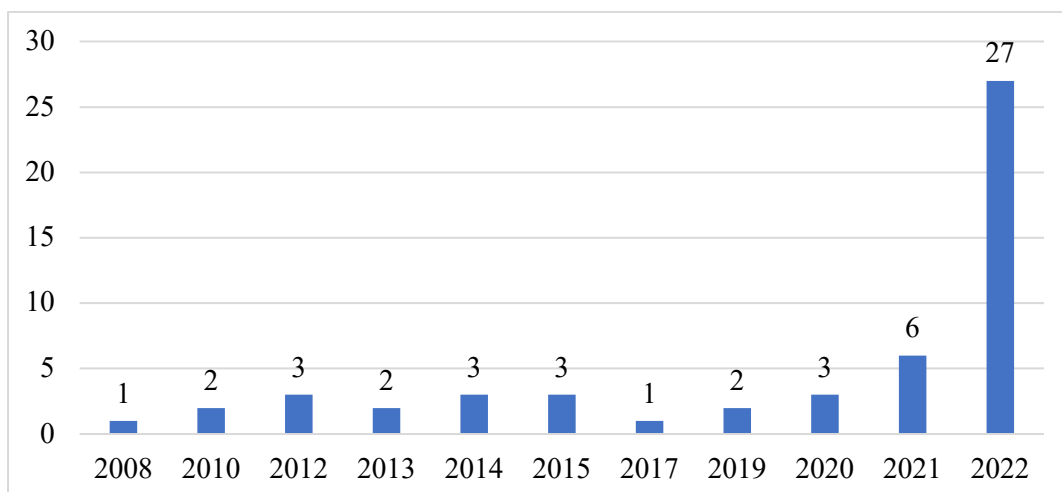


Figure 5.4: Publication years and number of studies

In the literature, research papers come to the fore in searches. While 10 of the 53 studies are review papers, the rest are research papers. According to the literature review of

academic studies, the articles until 2017 are only articles that explain the topics and general concepts. No analytical method is used in these articles. After 2017, methods such as statistical methods, neural networks, algorithms have been used and analyzes have been started.

The number of analytical methods used in the articles is small. In studies that use methods such as surveys and analyzes are made with statistical methods. Apart from these, it is seen that methods such as Fuzzy Markup Language, Computer-based Testing, Convolutional Neural Networks, Speech Recognition Algorithms, and Text Image Preprocessing Algorithm etc. are used in studies that focus on information systems. In addition, there are studies using AHP and simulation methods. However, there is no study that handles the metaverse-based education concept from an MCDM perspective.

There are many different fields of application areas such as medical education, physical education, language learning, higher education, primary education, secondary education, teacher education, gamification, nuclear safety education, virtual learning, engineering education, aircraft maintenance, art education etc.

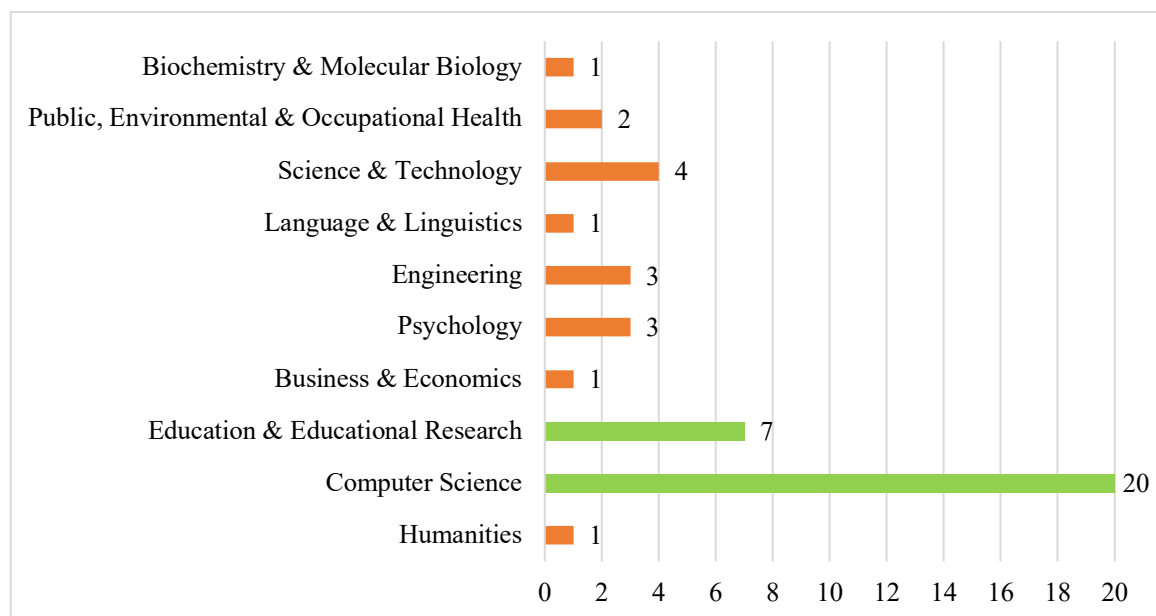


Figure 5.5: WoS categories

Another way to classify publications on the WoS database is to categorize them into WoS categories. In this context, the WoS category results of the research articles are as in Figure 5.5. There are two categories that stand out in this context: "Computer Science" and "Education & Educational Research". Most of the research articles seem to belong to the "Computer Science" category. The analytical techniques used also support this category. In review articles, 7 out of 10 articles belong to the "Education & Educational Research" category.

As can be seen in Table 5.2 and Table 5.3, many technologies that support metaverse-based education are used in studies. These digital technologies were classified to structure the investigation. A total of 53 articles were examined and the 14 most used technologies were identified. Figure 5.6 shows these technologies and how many studies have used these technologies.

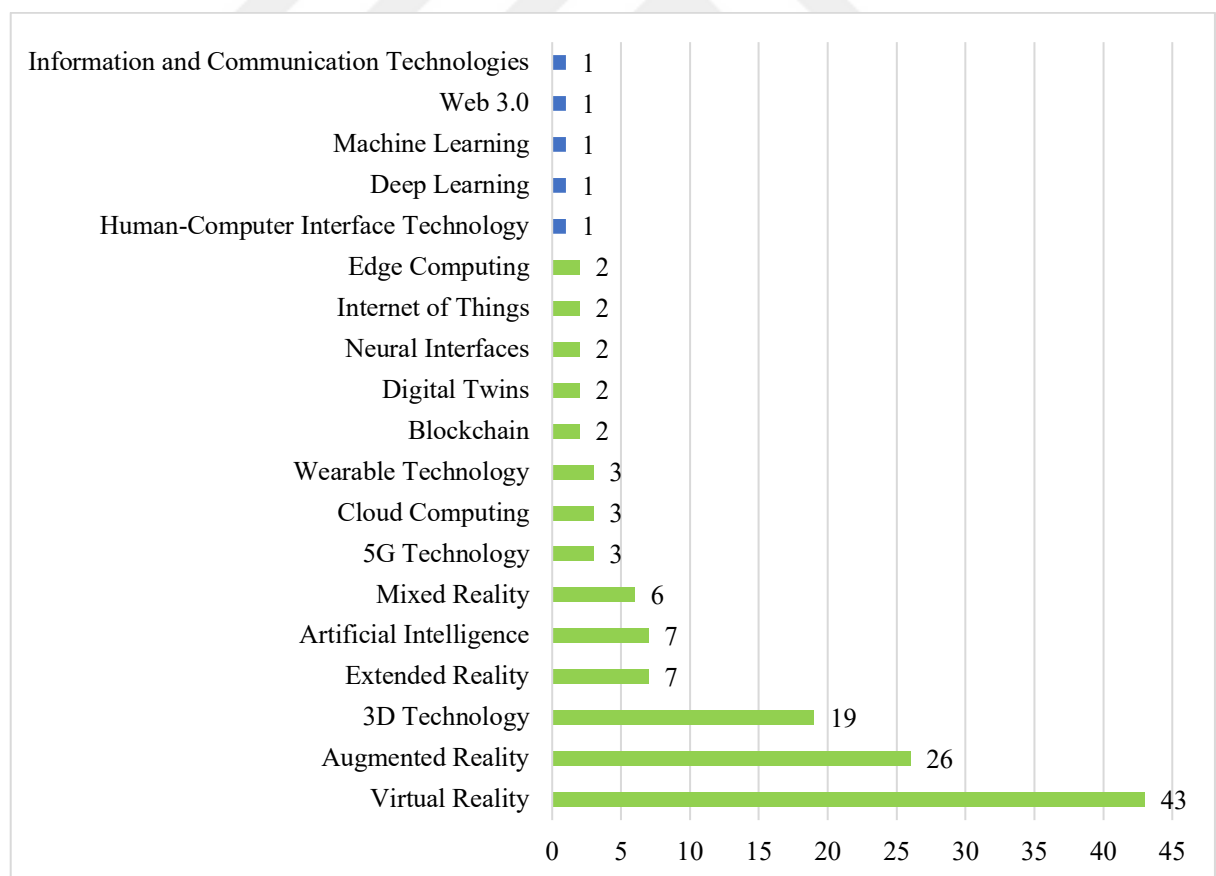


Figure 5.6: Distribution of technologies

As seen in Figure 5.6, the most discussed technologies in the articles are “Virtual Reality”, "Augmented Reality", and “3D Technology”. Following this, “Extended Reality”, “Artificial Intelligence”, and "Mixed Reality" are the most frequently mentioned technologies. These technologies will be explained in the following sections.

Figure 5.7 shows how the co-occurrence of terms in keywords was examined using VOSviewer to determine the emphasis and trends of "Metaverse and Education" research. The size of the labels and circles is determined by the number of co-occurrences. Lines illustrate key connections between terms, and their thickness and distance between terms indicate the strength of the linkage.

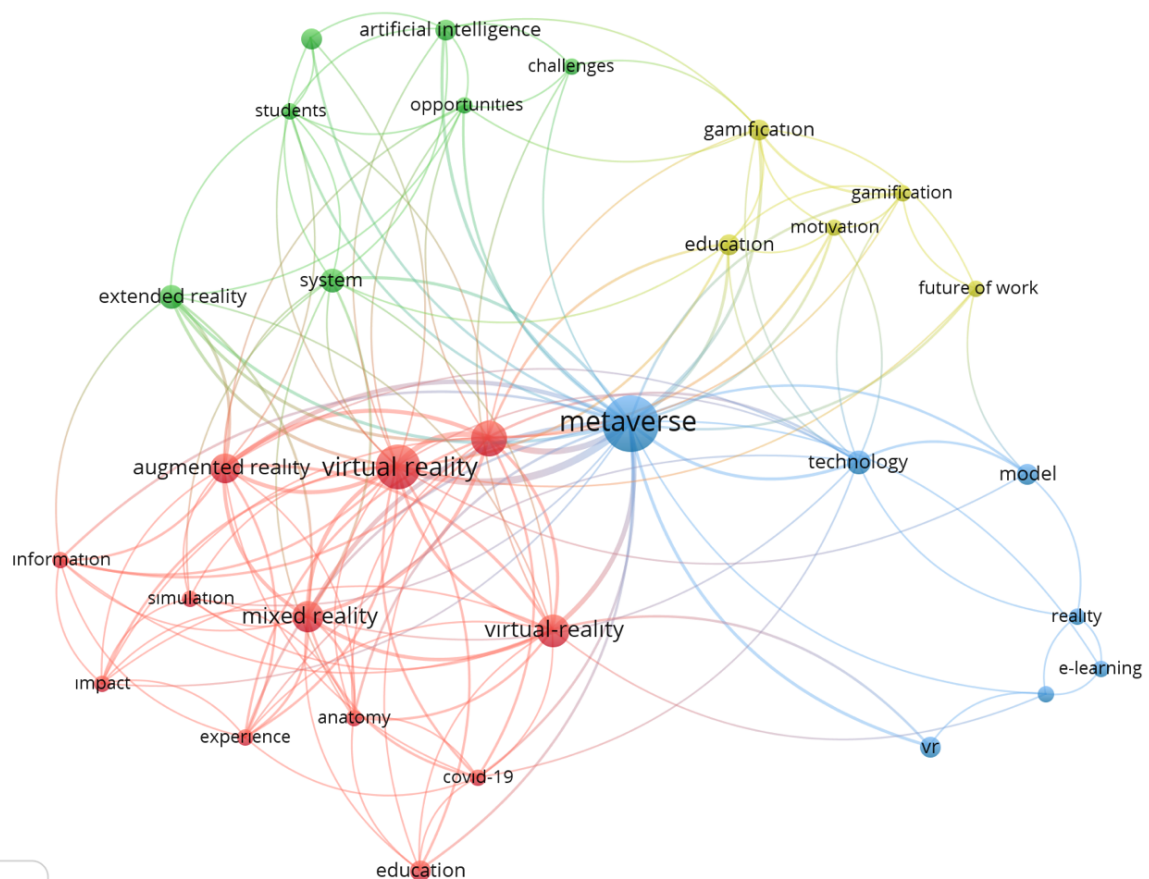


Figure 5.7: Keyword clustering for the “metaverse-based education” research

Furthermore, this figure indicates that the cluster distribution of database terms is nearly same (blue, green, red, and yellow clusters). The blue cluster is centered on "Metaverse"

and "technology," demonstrating the trend of using technology as a learning aid. Education and gamification are represented by the yellow cluster. The red cluster indicates Metaverse technology, which includes concepts such as augmented reality, virtual reality, simulation, and so on. The green cluster represents research trends in Metaverse issues in education.

As a result of the literature review, the research gaps of the studies are identified and categorized:

- In some studies, the metaverse-based education approach is only mentioned conceptually and these studies were not applied in any educational area. Schlemmer and Backes (2015) shared some research-related experiences in the framework of the digital education research group. Lee and Hwang (2022) introduced ground-breaking ideas into the fundamental area of sustainable education research. Chen (2022) investigated how the Metaverse platform may be used in the field of online education.
- Although some studies support the metaverse-based education approach with analytical methods, MCDM methods are not used even though the problem structure is appropriate. Jaramillo-Mujica et al. (2017) defined and analyzed the processes of scenario development, conception, and execution in the OpenSim platform with statistical methods. MacCallum and Parsons (2019) analyzed the teacher perspectives on mobile augmented reality with statistical methods and found that experienced teachers tended to concentrate on content. Lee et al. (2022) proposed a system that blends virtual reality and Metaverse approaches into the classroom to address the inadequacies of current remote education models by using simulation. Sun (2022) addressed book layout design and investigated how books are built at colleges and institutions with text image preprocessing algorithms.
- Although some studies in the literature address the metaverse-based education approach together with some technologies, they explain the technologies used in a limited way. Schaf et al. (2012) developed a prototype for learning environments by using 3D technology but they have not analyzed the uses of

this technology in metaverse-based education. Wagner et al. (2013) presented 3D virtual learning environments with vocational courses, delivered through programs, supported by the technologies used in distance education courses. Hedrick et al. (2022) presented the significance of facilitating a virtual classroom with only VR technology. An e-learning environment with a Metaverse framework with digital technologies was proposed by Dahan et al. (2022) but these technologies were not explained in detail.

- Although some of the studies in the literature address the benefits to users (students and instructors) of Metaverse-based education, the success and risk factors of this approach are not revealed. Nishino et al. (2012) investigated how the three e-learning modes affect the learners' learning preferences. Barry et al. (2015) evaluated students' learning manner using the eye blinking system in Metaverse. Park and Kim (2022) identified world types in the Metaverse to deliver a gameful experience to users. Ge (2022) defined multiple influences of intelligent technologies on students' behaviors.
- Although some of the studies in the literature provide frameworks for metaverse-based education, they do not mention the characteristics of metaverse-based education. Although Clark (2012) presented the virtual laboratory environment in Second Life, some of the key characteristics of metaverse-based education were not mentioned. Díaz et al. (2020) addressed the issue of the design, development, and implementation of a virtual or Metaverse world in an educational environment under the scrum methodology. Although Sandrone (2022) presented a new approach to medical education in a Metaverse environment, the essential features of this education were not specified.

In this context, in this study, these research gaps are categorized. The main gaps are identified and these gaps are tried to be filled.

5.1.5. Findings of Metaverse-based Education

The purpose of our extensive literature assessment was to identify the fundamental difficulties and information gaps identified in research on metaverse-based education.

We identified 53 articles and 8 industrial reports within this study. This literature review shows that the majority of the studies on Metaverse and education are conceptual studies explaining the subject and there is no study in the literature that reveals the success and risk factors in metaverse-based education and analyzes the technologies used. In this context, analyzes were made for the literature review, and the results were interpreted. According to these results, it is possible to say that the number of studies on this subject has increased in the last two years.

Hence, this section makes a number of observations about the application of metaverse-based education and highlights gaps in the research about the potential of metaverse-based education in addressing critical success and risk variables. According to the current study, there are various research gaps in the current literature dealing with metaverse-based education. These gaps are summarized in the following:

- *Lack of Characteristics on Metaverse-based Education*

When metaverse-based education is examined in the literature, there are many different studies that convey the features that Metaverse should have and how it can be applied in the field of education (Clark, 2012; Díaz et al., 2020; Sandrone, 2022). Kanematsu et al. (2014) presented an application for a virtual class for nuclear safety education in the Metaverse. Alvaro-Farfan et al. (2019) presented the usage of virtual worlds as an evaluation tool for students. Díaz (2020) presented the potential of a virtual world as an academic resource that motivates students in their training and teachers to develop new digital skills and competencies. However, there is no study in the literature that explains the features of metaverse-based education in detail.

- *Lack of Success Factors on Metaverse-based Education*

As a result of the literature review, studies on Metaverse and education were examined. There is no study examining critical success and risk factors of metaverse-based education in these studies that deal with this issue as a concept. Some studies address the benefits of metaverse-based education to users (Nishino et al., 2012; Barry et al.,

2015; Park & Kim; 2022). Rapanotti and Hall (2010) focused on the lessons learned from the viewpoint of managing the development of the learning environment. Masferrer et al. (2014) presented experiences teaching with distance seminars in Metaverses and videos. Ge (2022) defined multiple influences of intelligent technologies on students' behaviors. At this point, defining success factors will enable to progress with more reliable steps in the integration of Metaverse technology into education.

Since Metaverse is an expensive technology, it is necessary to make a careful decision and proceed with the right roadmap. As in many sectors, new technology trends in education promise a virtual world called "Metaverse" beyond the fact that teachers use traditional digital tools to show a picture or video in their lectures or read from books (Hirsh-Pasek et al., 2022). Metaverse is a technology that allows students to physically experience the information they read in traditional classrooms in a digitally simulated environment. This technology is made possible by the combination of augmented reality, virtual reality, and 3D technologies. Students can digitally experience the monuments, eras, explorations, and wars they read about in the books. Thus, Metaverse makes traditional learning very interesting and memorable (MacCallum, & Parsons, 2019; Hirsh-Pasek et al., 2022; Sandrone, 2022). There are many factors to consider in order for this technology to be properly integrated. In this way, it will be easier to bring success while making a high-cost investment.

- *Lack of Risk Factors on Metaverse-based Education*

Metaverse-based education, like other technology-based approaches, brings with it some risks. Various problems can arise when implementing metaverse-based education. In order to create a Metaverse environment, high Internet infrastructure, more technological computers, wearable technologies, and energy are required. Therefore, high equipment cost is an obstacle to the widespread use of Metaverse. The risks associated with augmented reality can be expressed in the form of physical well-being, health, safety, psychological, moral and ethical, and data privacy (Kye et al., 2021; Hwang & Chien, 2022).

The absence of facial expressions in the virtual classroom in the Metaverse environment is the biggest risk for teaching. The instructor's and students' lack of emotion can be a severe issue in virtual learning. Consequently, whether in real life or in the virtual world, facial expressions are frequently one of the most important factors for discussion. The Internet connection must be good so that the virtual world does not slow down or disconnect. Likewise, user equipment that wants to take advantage of the virtual world should have good hardware both in terms of processing capacity and graphics card (Mustafa, 2022; Park & Kim, 2022). Ethics for education in the digital environment is a broad topic that needs attention at different levels of education. Containing concepts such as privacy, social harassment, and accessibility, it constitutes one of the biggest risks (Mangina, 2021).

There are studies in the literature that specifically address the problems that may be encountered in integrating the Metaverse into the education system. Kanematsu et al. (2010) presented a multilingual discussion environment in Metaverse with students from the USA, Korea, and Japan. Zhang et al. (2022) introduced the visions of the Metaverse in education with definitions, frameworks, features, potential applications, challenges, and future research topics. Tlili et al. (2022) conducted a systematic literature review of the Metaverse in education as a concept blessing or a curse. Stanoevska-Slabeva (2022) presented the concept of Metaverse for education with opportunities and challenges.

- *Lack of Technology Analysis on Metaverse-based Education*

Although Metaverse is referred to as a new technology, it is actually a collection of technologies. It is described as a platform for the convergence of several novel and advanced technologies. The statements made show that augmented reality, virtual reality, artificial intelligence, neural interfaces, blockchain applications, and wearable electronic products will play a major role in the establishment of the Metaverse universe (Chen, 2022; Lee & Hwang, 2022; Rospigliosi, 2022b).

While metaverse-based education is being implemented, supporting it with other technologies facilitates the integration process. As seen in Tables 5.2, 5.3, and 5.4, which were created as a result of the literature review, there are many technologies on which Metaverse is based. Virtual reality, augmented reality, and 3D technology are the most widely used technologies in the literature together with metaverse-based education (Kanematsu et al., 2010; Rapanotti & Hall, 2010; Schaf et al., 2012; Bilhao Gomes & Klein, 2013; MacCallum & Parsons, 2019; Siyaev & Jo, 2021; Almarzouqi et al., 2022; Dahan et al., 2022). Clark (2012) presented a virtual laboratory environment by using virtual reality. Wagner et al. (2013) presented 3D virtual learning environments. Kanematsu et al. (2014) presented an application for a virtual using virtual reality. Augmented reality technology is used in many different fields such as the evaluation of primary education practice, determining students' perceptions of the use of Metaverse in their learning experiences, and examining teacher perspectives on mobile augmented reality (MacCallum & Parsons, 2019; Reyes, 2020; Lopes & Gonçalves, 2021). However, there is no study in the literature that analyzes these technologies and indicates how often they are used in which areas.

- *Lack of Multi-Criteria Decision-Making Methods on Metaverse-based Education*

Based on the review of the research, it is possible to deduce that statistical approaches, neural networks, simulation, and so on predominate. As a result of the literature review, the studies in Table 5.2 show that statistical methods are frequently used as analytical methods (Jaramillo-Mujica et al., 2017; MacCallum & Parsons, 2019; Reyes, 2020; Park et al., 2021; Almarzouqi et al., 2022; Jovanović & Milosavljević, 2022; Suh & Ahn, 2022; Lee et al., 2022; Lo et al., 2022; Iwanaga et al., 2022). In addition, algorithms such as text image preprocessing algorithms, speech recognition algorithms, and fuzzy markup language are analytical methods used in metaverse-based education (Siyaev & Jo, 2021; Lee et al., 2022; Sun, 2022). Convolutional neural networks are used for aircraft maintenance Metaverse using speech interactions with virtual objects in mixed reality and metaverse-powered English teaching design (Siyaev & Jo, 2021; Guo & Gao, 2022).

Although some studies support the metaverse-based education approach with analytical methods, MCDM methods are not used even though the problem structure is appropriate. MCDM methods based on expert opinions might throw light on the gap in this sector. Group decision-making procedures, in particular, may be paired with analytical tools to better deal with uncertainty, contradicting indicators, and linguistic judgments. Furthermore, by reducing uncertainties, the use of fuzzy techniques in decision-making procedures would aid in the solution of increasingly difficult and complicated issues with more exact answers. Numerous articles in different fields of research integrate MCDM techniques with group decision-making and/or fuzzy methodologies, which can add to the metaverse-based education literature.

5.2. Proposition of Metaverse-based Education System with Integrated QFD Approach

Metaverse-based education, which is at its starting point, needs digital technologies to develop and complete its maturity. In this context, it is necessary to examine these technologies and determine the most suitable technology for Metaverse. In the literature, there are very few studies that deal with Metaverse together with other technologies. Lee and Hwang (2022) presented technology-enhanced education with VR technology and Metaverse to develop teacher readiness and sustainable learning. Chen (2022) explores the application issues facing Metaverse technology in education. The technology acceptance model is proposed for students' intention of using Metaverse for basketball learning by Ren et al. (2022). Yenduri et al. (2023) show the role of assistive technologies in higher education for students with learning difficulties. Al-Adwan et al. (2023) recommend employing metaverse-based learning platforms to forecast university students' intents using a technology acceptance model.

In this thesis, the digital technologies are evaluated for metaverse-based education. It is seen that an analytical approach is not integrated into this subject in the studies in the literature. In this chapter, the fermatean fuzzy AHP-based QFD methodology with aggregation operators is proposed as an analytical approach. Thus, this gap in the literature has been filled.

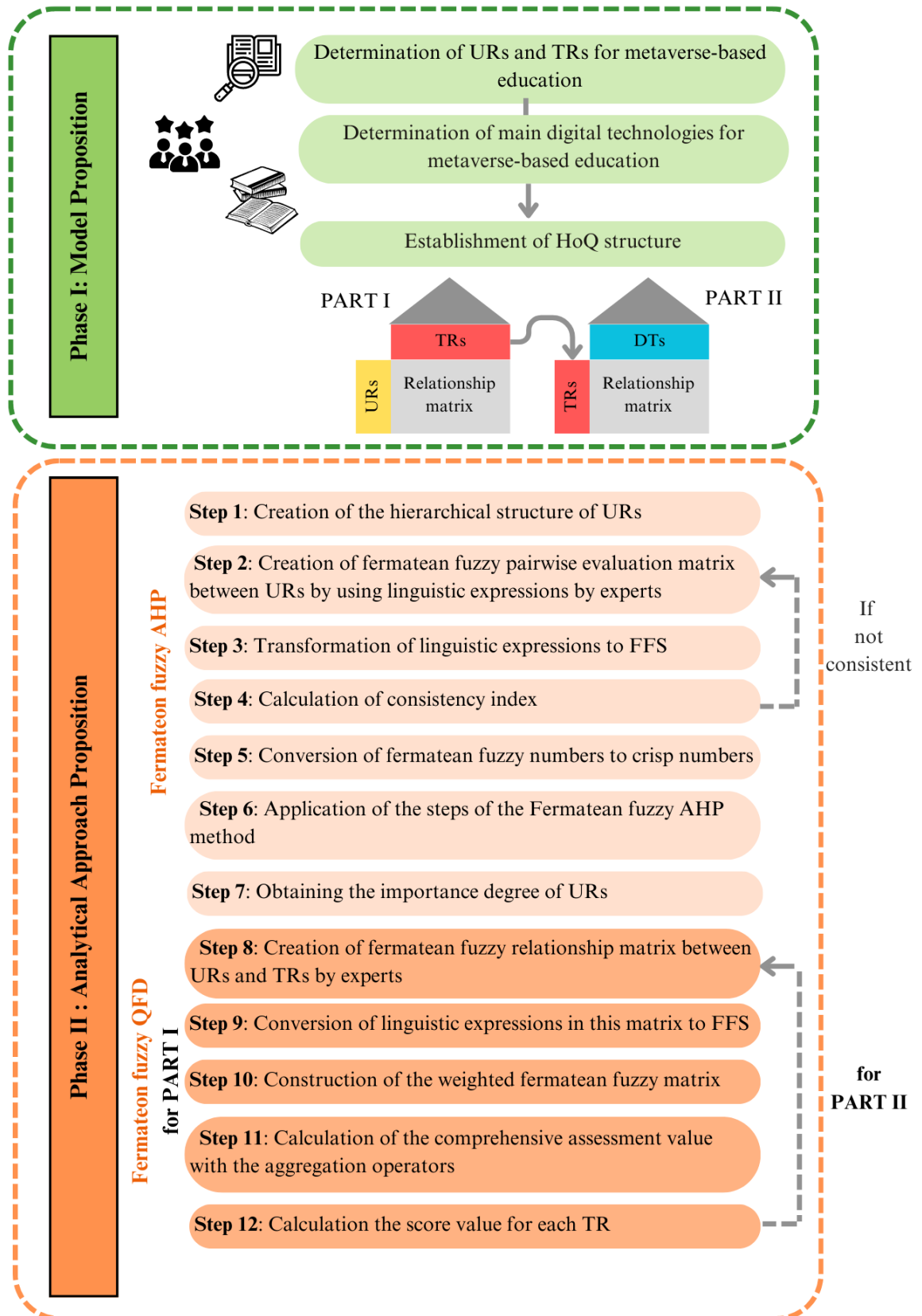


Figure 5.8: Framework of the proposed metaverse-based education system

In this chapter, the proposed research methodology is illustrated in Figure 5.8. In this methodology, there are two phases: the proposed evaluation model and the proposed analytical approach. First of all, the URs and TRs are determined by examining academic papers, industrial reports, and experts' opinions. The relationships between these requirements have been revealed with the QFD approach, and the TRs have been prioritized with the proposed analytical approach. Then, the same steps were applied and the relationships between TRs and main digital technologies were determined. Finally, the main digital technologies for metaverse-based education are assessed with the proposed analytical approach. All relationships in the evaluation process were determined by the experts. In this study, the fermatean fuzzy AHP-based QFD methodology with aggregation operators is proposed as an analytical approach.

The assessment model for metaverse-based education consists of components such as URs, TRs, and main digital technologies. These components are presented in the next sections.

5.2.1. User Requirements of Metaverse-based Education

The URs determined as a result of the literature review and expert opinions within the scope of the study are as in Table 5.5.

Table 5.5: URs of metaverse-based education

URs	Explanation	References
• User-based		
○ Emotional engagement	users' involvement in and enthusiasm for metaverse-based education	(Ball, 2020; Zhou, 2022)
○ Self-sovereign and interoperable digital identity	persona that the user can use to interact with herself/himself or other users in the digital environment	(Zhang et al., 2022; Lo & Tsai, 2022)
○ User interactivity	communication of the user with the system or other users in the system	(Díaz et al., 2020; Kye et al., 2021; Jovanović & Milosavljević, 2022; Lo & Tsai, 2022)
○ Immersive and multisensory experience	experience across a journey, or task that's contextually relevant, enabled by a combination of interactions that create intuitive and emotional value for the user	(Ball, 2020; Zhang et al., 2022)
○ Decentralized and editable content	a form of content distribution that seeks to eliminate intermediaries, allowing each user to directly receive the real benefits that their content has generated	(Kye et al., 2021; Tlili et al., 2022)
○ Digital literacy	ability to navigate the digital world using reading, writing, technical skills, and critical thinking	(Zhou, 2022; Thinktech, 2022)
○ User interface esthetics	reasonable, standard, and suitable interface layout for the virtual world	(Hammad, 2018; Ortega-Rodríguez, 2022)

Table 5.5: URs of metaverse-based education (*continue*)

URs	Explanation	References
• Technology-based		
○ Real-time monitoring	technique that allows you to determine the current state of queues and channels within a queue manager	(Ortega-Rodríguez, 2022)
○ Convergence of the virtual and real world	increasing resemblance of virtual world reality to real world	(Ball, 2020; Ortega-Rodríguez, 2022)
○ Rapid and free access	to be accessible quickly and free of charge	(Zhang et al., 2022; Thinktech, 2022)
○ Synchronous and live	to be in real-time	(Ortega-Rodríguez, 2022)
○ Access to information resources	to offer all kinds of educational materials to the user	(Tlili et al., 2022; Zhou, 2022)
• System-based		
○ Security & privacy	the system to be safe from hackers or cybercriminals and the confidentiality of the system against protected information	(Mystakidis, 2022; Jovanović & Milosavljević, 2022; Thinktech, 2022)
○ Trust & accountability	the confidence that the system places on the user, and the obligation or willingness to account for her/his actions	(Hammad, 2018; Kye et al., 2021; Thinktech, 2022)
○ Functionality	easy and comfortable use of the system by users	(Hammad, 2018; Ball, 2020; Ortega-Rodríguez, 2022)

○ Flexibility & adaptability	the system to be flexible and easily adaptive to all kinds of educational issues	(Hauge et al., 2006; Zhang et al., 2022; Thinktech, 2022)
○ Open to everyone	the system to be accessible to everyone	(Hirsh-Pasek et al., 2022; Zhang et al., 2022)
○ Technical stability	constancy and balance of the educational environment	(Hammad, 2018; Jääskä et al., 2022)
○ Fault and uncertainty tolerance	degree to which a system or component operates as intended despite the presence of hardware or software faults and uncertainties	(Hammad, 2018; Jääskä et al., 2022)
○ Interoperability	the degree to which two or more systems or components can exchange information and use the information that has been exchanged	(Hammad, 2018; Kye et al., 2021)
○ Install ability & Maintainability	system can be successfully installed and/or uninstalled in a specified environment and modified by the intended maintainers	(Hammad, 2018; Jääskä et al., 2022)

Table 5.5: URs of metaverse-based education (*continue*)

URs	Explanation	References
• Organizational-based		
○ Resource management	managing all resources of the educational environment	(Hammad, 2018; Tlili et al., 2022; Zhou, 2022)
○ Simultaneous report generation	reporting the activity of the virtual world at the moment it takes place	(Hwang & Chien, 2022)
○ Course scheduling	planning user-specific lessons	(Zhou, 2022; Thinktech, 2022)
○ Promoting interdisciplinary studies	bringing together users from different institutions or different departments by making use of the ability of virtual environments to easily unite users	(Hirsh-Pasek et al., 2022; Zhou, 2022)
○ Cooperation and sharing	communication and collaboration of all stakeholders in the system with each other	(Zhou, 2022; Ge, 2022; Stanoevska-Slabeva, 2022)
○ Feedback mechanism	information that is given to the users about the users' performance relative to learning goals or outcomes	(Hwang & Chien, 2022; Hirsh-Pasek et al., 2022; Zhang et al., 2022)

5.2.2. Technological Requirements of Metaverse-based Education

The TRs determined as a result of the literature review and expert opinions within the scope of the study are as in Table 5.6.

Table 5.6: TRs of metaverse-based education

TRs	References
Hardware infrastructure (TR1)	(Kye et al., 2021; Shu & Gu, 2023)
Computer network (TR2)	(Ge, 2022; Shu & Gu, 2023)
High-speed communication and networks (TR3)	(Jovanović & Milosavljević, 2022)
Decentralized data storage (TR4)	(Zhou, 2022; Tlili et al., 2022)
Virtual world design (TR5)	(Jovanović & Milosavljević, 2022; Queiroz et al., 2023)
Full body avatar design and control (TR6)	(Kye et al., 2021; Jovanović & Milosavljević, 2022)
3D models and environments (TR7)	(Jovanović & Milosavljević, 2022; Dahan et al., 2022)
Data transfer and transaction verification mechanism (TR8)	(Dahan et al., 2022; Deloitte, 2022; Shu & Gu, 2023)
IoT network communication support (TR9)	(Deloitte, 2022; Queiroz et al., 2023)
5G/6G Network (TR10)	(Deloitte, 2022; Chow et al., 2022)
Perceptual interaction technology (immersive audio, tactile feedback, speech recognition, eye tracking) (TR11)	(Deloitte, 2022; Hwang & Chien, 2022)
Authentication (TR12)	(Pimentel et al., 2022)
Consensus mechanism (TR13)	(Ge, 2022; Tlili et al., 2022)
Hashing and timestamp technology (TR14)	(Deloitte, 2022; Hwang & Chien, 2022)
VR technology (TR15)	(Deloitte, 2022; Zhou, 2022; Queiroz et al., 2023)

Table 5.6: TRs of metaverse-based education (*continue*)

TRs	References
AR technology (TR16)	(Deloitte, 2022; Zhou, 2022; Shu & Gu, 2023)
MR technology (TR17)	(Deloitte, 2022; Zhou, 2022)
Holographic display (TR18)	(Deloitte, 2022; Pimentel et al., 2022; Tlili et al., 2022)
Hybrid cloud rendering (TR19)	(Deloitte, 2022; Queiroz et al., 2023)
Game engine (TR20)	(Deloitte, 2022; Chow et al., 2022)
Network transmission technology (TR21)	(Deloitte, 2022; Pimentel et al., 2022; Tlili et al., 2022)
Simulation (TR22)	(Li et al., 2022; Queiroz et al., 2023)
Human-machine interaction (TR23)	(Chow et al., 2022; Shu & Gu, 2023)
Robotic Process Automation (TR24)	(Chow et al., 2022; Queiroz et al., 2023)

5.2.3. Digital Technologies of Metaverse-based Education

Education is affected by the destructive transformation of technology and becomes a part of the transformation. Metaverse is one of the most important technologies of this transformation process in recent years. In this context, metaverse-based education, which is still at its starting point, is supported with the right and efficient digital technology and it is aimed to continue education efficiently. Detailed information about main digital technologies integrated metaverse-based education is given below:

- *Network and Computing Technologies:* Network and computing technology covers all technologies, including communication and computers, which are used to collect, process, store information, transmit it from one place to another via networks and present it to the service of users. Metaverse needs real-time

networks to run compute-intensive tasks remotely, communicate between automated systems, access large databases, or deliver shared experiences among users. This technology provides real-time big data and high-resolution image streaming for existing and planned Metaverse applications. In addition, the bandwidth must be extremely wide for the data to be transmitted (Lopes & Gonçalves, 2021; Thinktech, 2022; JP Morgan, 2022).

- *Blockchain*: The technology that will allow the Metaverse to be decentralized, interoperable, and secure. Blockchain technology includes topics such as data storage, data interoperability, and data sharing, as well as offering a technological infrastructure in cryptocurrencies that create a virtual economy in the Metaverse. Blockchain technology is required to guarantee the reliability of data processed with AI algorithms in the Metaverse. It can be said that the blockchain is a technology that gives confidence in transactions between individuals (Damar, 2021; Thinktech, 2022; Deloitte, 2022).
- *Internet of Things (IoT)*: Physical item network that communicates with one another and can facilitate physical/virtual integration. This technology refers to the connected tools in the IoT, a world where data is collected and devices interact with each other, and human-robot interaction is possible. Metaverse needs a strong informatics and telecommunication infrastructure. It needs to be intertwined with IoT applications in order to build a bridge between physical reality and digital reality. IoT devices that can collect all kinds of measurable data in all areas of life without the need for human intervention, and algorithms that convert them into actionable information by analyzing them will make the Metaverse a perfect reality (Deloitte, 2022; EY, 2022; JP Morgan, 2022).
- *Immersive and Interaction Technologies*: Immersive and interaction technologies (VR, AR, MR) refer to technologies that try to imitate a physical world through a digital or simulated world by creating a sense of reality. Metaverse is a network of interconnected and interconnected immersive environments across multi-user platforms. These technologies are among the most important technologies required for the realization of the Metaverse. While AR can overlay and superimpose digital information onto the physical medium,

VR allows users to experience the digital world vividly (Damar, 2021; Deloitte, 2022; Hwang & Chien; 2022).

- *AI Technology*: AI is another important and critical technology within the Metaverse. It allows avatars to act autonomously in created scenarios, allowing avatars to maintain their behavior with AI elements. AI can enable the development of systems that are sensitive to people, objects and actions that can provide real-time and valuable information to Metaverse users (Damar, 2021; Thinktech, 2022; Hwang & Chien; 2022; JP Morgan, 2022).
- *Digital Twin*: A virtual equivalent of a physical thing or process that may be utilized to construct Metaverse worlds in real-time. A digital twin is employed in the Metaverse to digitize real-world things and place them in the virtual environment in real-time. Certain projects in Metaverse schooling demand great precision, with rigorous criteria on the accuracy and real-time performance of digital twins. This means that digital twins should be able to detect and correct faults. Another significant problem of digital twins is data security and privacy while developing digital twin models utilizing real-time data (Lin et al., 2022; Deloitte, 2022).

5.3. Application of the Proposed Approach

Metaverse's learning opportunities that go beyond the limits of Internet technology go beyond the benefits of e-learning. In the new era in which distance-based education transforms the type of education, the Metaverse is expected to offer faster and more effective development opportunities. At this point, technology in education plays a supportive, balancing, and auxiliary role for different learning styles and different learner characteristics. In this respect, technology has the potential to contribute to increasing the quality of life of individuals with special needs as well as all individuals.

In this thesis, the main digital technologies are evaluated to improve the quality of metaverse-based education and to support its development. As a result of the literature review and expert opinions for this evaluation, a model consisting of URs and TRs was created. URs consist of four main requirements and 27 sub-requirements such as user-

based, technology-based, system-based, and organizational-based. In addition, there are 24 TRs in the model. In addition, this study includes six main digital technologies that support metaverse-based education such as Networking and Computing Technologies (DT1), Blockchain (DT2), IoT (DT3), Immersive and Interaction Technologies (DT4), AI Technology (DT5), and Digital Twin (DT6). The fermatean fuzzy QFD approach integrated with aggregation operators is used for the evaluation of TRs and main digital technologies by obtaining the importance degree of URs with the fermatean fuzzy AHP method.

All evaluations are made by three professionals and three academics who are experts in their fields. The first expert owns his technology company and practices in the field of digital transformation. The second expert has digitalization experience and offers certified education programs on digital platforms and institutions. The third expert has also worked in the private sector and is a guest lecturer at universities. Academics are people who teach in the engineering faculty and work on digital transformation, digitalization, etc.

In the first phase, URs, TRs, and main digital technologies are determined with the literature review of academic papers and industrial reports, and experts' opinions.

In the second phase, firstly, the hierarchical structure of URs is constructed as in Figure 5.9. The experts evaluated the main URs via the linguistic scale presented in Table 3.6. Table 5.7 shows fermatean fuzzy pairwise evaluation matrix between URs with linguistic expressions. These expressions are converted to FFS. Then, the fermatean fuzzy number are transformed to crisp numbers with (3.4.22). These $S(\mathcal{F})$ values are shown in Table 5.7.

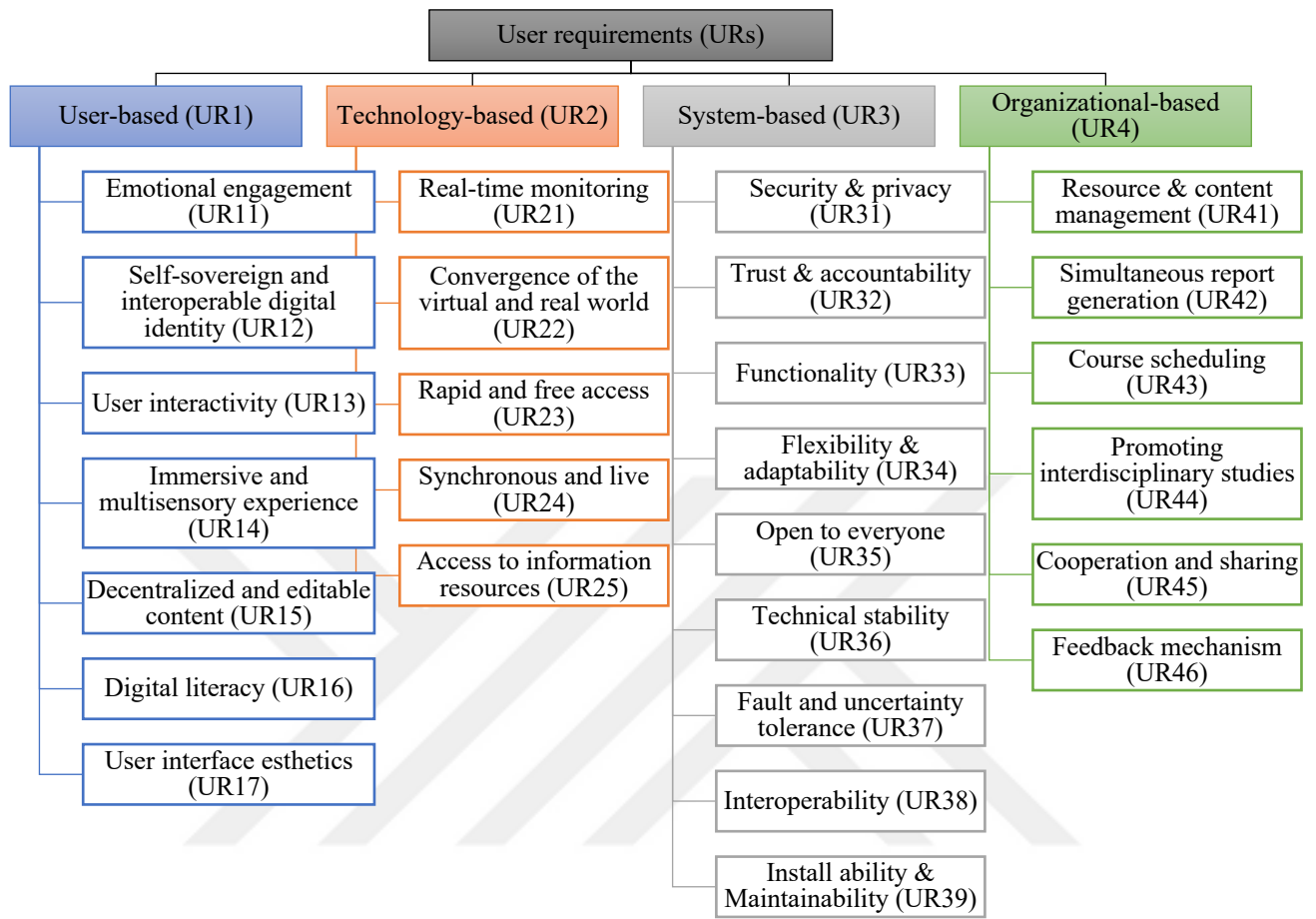


Figure 5.9: URs of metaverse-based education

In order to check the consistency, CR is calculated for the pairwise comparison matrix of main URs with equations (3.4.23)-(3.4.27). As the CR is 0.005 for main URs, DMs' evaluations are highly satisfactory.

Table 5.7: Evaluation matrix for the main URs and $S(\mathcal{F})$ values

	Main URs				$S(\mathcal{F})$ values				
	UR1	UR2	UR3	UR4		UR1	UR2	UR3	UR4
UR1	-	MH	VH	MH	UR1	1	1.052	0.762	1.052
UR2		-	MH	A	UR2		1	1.052	1.246
UR3			-	VL	UR3			1	1.460
UR4				-	UR4				1

The pairwise comparison matrices of the sub-URs are created in the same way as shown in Table 5.7. The steps of the fermatean fuzzy AHP is applied and the global importance degrees of the sub-URs are obtained as in Table 5.8. These weights are found by multiplying the importance degrees of main URs and the relative importance degrees of the sub-URs.

At the end of the fermatean fuzzy AHP method, the results indicate that “rapid and free access (UR23)” is the most appropriate expectation followed by “access to information resources (UR25)”. Similarly, “synchronous and live (UR24)” is obtained as the third-ranked expectation. The importance degrees of the main URs are illustrated in Figure 5.10.

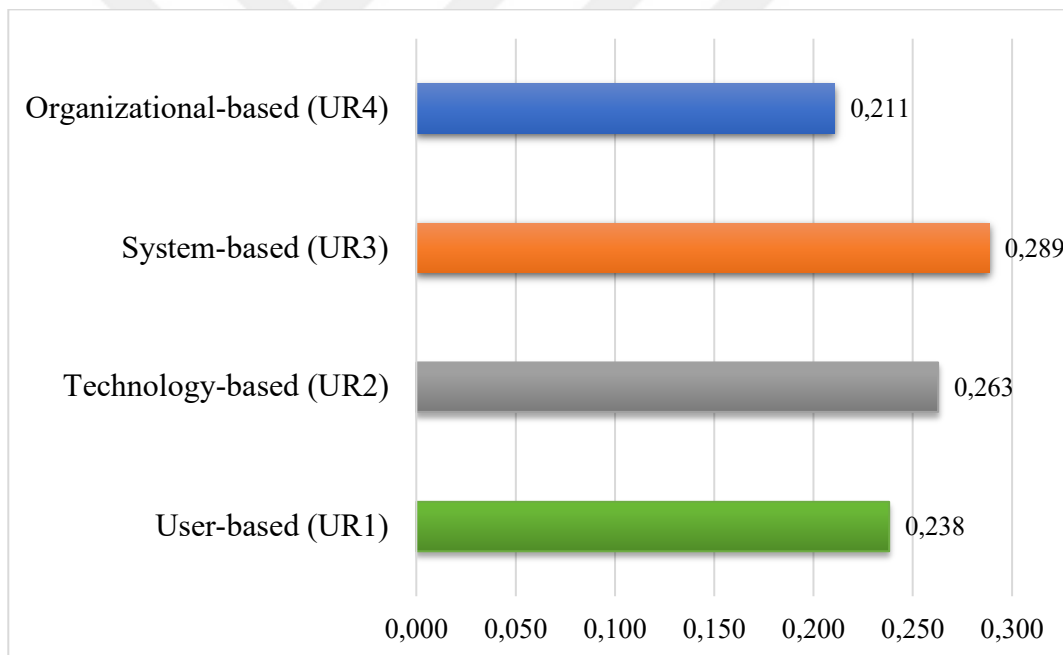


Figure 5.10: Importance degrees of the main URs

Secondly, the HoQ concept is structured and the relationship matrix between URs and TRs is created by experts with linguistic expressions as in Table 5.9. These expressions are converted to FFS. Then, the weighted fermatean fuzzy matrix is computed by multiplying the importance degrees of URs and fermatean fuzzy evaluation matrix as in Table 5.10.

Table 5.8: Final importance degrees of URs

Main URs	Importance degrees of main URs	Sub-URs	Relative importance degree	Global importance degree	Ranking
UR1	0.238	UR11	0.143	0.0341	16
		UR12	0.164	0.0390	10
		UR13	0.119	0.0284	22
		UR14	0.107	0.0254	26
		UR15	0.120	0.0285	21
		UR16	0.179	0.0426	7
		UR17	0.168	0.0400	8
UR2	0.263	UR21	0.201	0.0527	4
		UR22	0.146	0.0383	11
		UR23	0.226	0.0593	1
		UR24	0.204	0.0536	3
		UR25	0.224	0.0588	2
UR3	0.289	UR31	0.129	0.0371	12
		UR32	0.123	0.0354	14
		UR33	0.093	0.0270	23
		UR34	0.089	0.0257	25
		UR35	0.101	0.0292	19
		UR36	0.124	0.0358	13
		UR37	0.118	0.0340	17
		UR38	0.085	0.0246	27
		UR39	0.138	0.0399	9
UR4	0.211	UR41	0.127	0.0268	24
		UR42	0.221	0.0465	5
		UR43	0.205	0.0432	6
		UR44	0.168	0.0354	15
		UR45	0.137	0.0288	20
		UR46	0.142	0.0299	18

Table 5.9: Relationship matrix between URs and TRs

	TRs																
URs	TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	.....	TR17	TR18	TR19	TR20	TR21	TR22	TR23	TR24
UR1																	
UR11	A	ML	ML		H	VH	H		.....	MH	AH	MH	A	L	H	VH	A
UR12	VH	VH	A	H	ML	AH	ML	H	.....	H	A	H	A	H	A	A	A
UR13	AH	A	VH	A	H	A	H	L	.....	MH	A	H	H	A	H	VH	A
UR14	VH	A	AH	A	VH	VH	AH	H	.....	VH	AH	MH	VH	A	MH	AH	A
UR15	H	VH	MH	VH	MH		H	MH	.....	AL	AL	AL	MH	MH	VL	VL	MH
UR16	A	L	AL		A				.....	A	VL	L	L	ML	VL	H	H
UR17	AH	MH	VH		VH	H	VH		.....	VH	VH	VH	VH	A	A	H	A
UR2																	
UR21	VH	H	AH					VH	.....	A				AH		ML	A
UR22	VH	H	AH		VH	H	VH	MH	.....	VH	AH	VH	AH	AH	H	VH	A
UR23	AH	MH	AH	ML				AH	.....	AL	AL	AL	VL	H	ML	A	A
UR24	MH	H	VH					AH	.....	VL	VL	AL	AL	H	ML	A	A
UR25	A	A	H	AL	A			H		A	A	A	A	H	AL	A	A

Table 5.9: Relationship matrix between URs and TRs (*continue*)

	TRs																
URs	TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	.....	TR17	TR18	TR19	TR20	TR21	TR22	TR23	TR24
UR3																	
UR31	MH	MH	H	H				H	.....					A		ML	L
UR32	H	H	A	A				MH	.....					H		VL	ML
UR33	H	A	A	ML	L	ML		H	.....	H	H	H	H	MH	L	AH	VH
UR34	MH	MH	A	A	ML			A	.....					H		AH	MH
UR35	MH	VH	AH	L	L			AH	.....					MH		A	A
UR36	VH	AH	VH					AH	.....					H		A	A
UR37	A	A	A	ML				VH	.....					ML		L	H
UR38	VH	H	A	L				AH	.....					AH		H	A
UR39	H	MH	AH	A				VH	.....					MH		ML	VH
UR4																	
UR41	MH	A	A	H	H	L	H	VH	.....	MH	MH	H	MH	MH	H	MH	MH
UR42	A	H	A					H	.....					A			VH
UR43	A	A	VL						.....							A	VH
UR44	VL	A	AL		VL		AL	A	.....	H	L	A	ML		L	AL	MH
UR45	H	H	MH	A	A	A	A	MH	.....	MH	MH	H	A	H		H	A
UR46	MH	A	MH			VL	AL	MH	.....					A		MH	AH

Table 5.10: Weighted fermatean fuzzy matrix for TRs

	TR1		TR2		.....		TR22		TR23		TR24	
UR11	0.210	0.979	0.169	0.989	.....	.....	0.290	0.962	0.290	0.962	0.210	0.979
UR12	0.456	0.860	0.456	0.860	.....	.....	0.220	0.976	0.220	0.976	0.220	0.976
UR13	0.526	0.605	0.198	0.982	.....	.....	0.273	0.968	0.273	0.968	0.198	0.982
UR14	0.400	0.900	0.191	0.984	.....	.....	0.296	0.947	0.296	0.947	0.191	0.984
UR15	0.273	0.968	0.527	0.604	.....	.....	0.092	0.996	0.061	0.998	0.307	0.941
UR16	0.226	0.974	0.143	0.991	.....	.....	0.070	0.998	0.350	0.917	0.311	0.953
UR17	0.579	0.551	0.305	0.956	.....	.....	0.222	0.976	0.343	0.921	0.222	0.976
UR21	0.499	0.827	0.374	0.901	.....	.....			0.196	0.984	0.243	0.968
UR22	0.572	0.558	0.301	0.958	.....	.....	0.338	0.924	0.454	0.862	0.219	0.977
UR23	0.641	0.493	0.346	0.937	.....	.....	0.203	0.982	0.252	0.965	0.252	0.965
UR24	0.376	0.899	0.376	0.899	.....	.....	0.154	0.989	0.244	0.968	0.244	0.968
UR25	0.252	0.965	0.252	0.965	.....	.....	0.118	0.993	0.252	0.965	0.252	0.965
UR31	0.298	0.959	0.335	0.926	.....	.....			0.136	0.992	0.174	0.988
UR32	0.330	0.929	0.330	0.929	.....	.....			0.099	0.996	0.134	0.993
UR33	0.268	0.969	0.195	0.983	.....	.....	0.123	0.994	0.407	0.895	0.407	0.895
UR34	0.264	0.971	0.264	0.971	.....	.....			0.511	0.621	0.264	0.971
UR35	0.310	0.940	0.417	0.888	.....	.....			0.200	0.982	0.200	0.982
UR36	0.444	0.869	0.561	0.569	.....	.....			0.214	0.978	0.214	0.978
UR37	0.210	0.979	0.210	0.979	.....	.....			0.132	0.993	0.325	0.931
UR38	0.505	0.627	0.260	0.972	.....	.....			0.260	0.972	0.189	0.985
UR39	0.305	0.956	0.305	0.956	.....	.....			0.178	0.988	0.578	0.552
UR41	0.268	0.970	0.194	0.983	.....	.....	0.268	0.970	0.301	0.944	0.301	0.944
UR42	0.233	0.972	0.360	0.910	.....	.....					0.481	0.841
UR43	0.227	0.974	0.227	0.974	.....	.....			0.227	0.974	0.591	0.540
UR44	0.099	0.996	0.213	0.978	.....	.....	0.134	0.993	0.099	0.996	0.293	0.961
UR45	0.308	0.941	0.274	0.967	.....	.....			0.308	0.941	0.199	0.982
UR46	0.312	0.939	0.201	0.982	.....	.....			0.278	0.966	0.534	0.597

Then, these values are aggregated with FFDWPM operator defined in (3.2.6). All calculations in (3.2.6) are based on the fermatean fuzzy Dombi operator calculations. The obtained comprehensive assessment values and score values are shown in Table 5.11.

Table 5.11: Comprehensive assessment values and score values for TRs

TRs	Comprehensive assessment values		Score values
TR1	0.2058	0.9545	-0.8609
TR2	0.1340	0.9993	-0.9956
TR3	0.2184	0.9989	-0.9863
TR4	0.0619	0.9995	-0.9981
TR5	0.1405	0.9989	-0.9940
TR6	0.0833	0.9985	-0.9951
TR7	0.1376	0.9834	-0.9484
TR8	0.2011	0.9996	-0.9908
TR9	0.1354	0.9997	-0.9966
TR10	0.2074	0.9987	-0.9871
TR11	0.0987	0.9988	-0.9954
TR12	0.1381	0.9979	-0.9911
TR13	0.1502	0.9999	-0.9963
TR14	0.1463	0.9993	-0.9947
TR15	0.1097	0.9989	-0.9955
TR16	0.1441	0.9998	-0.9963
TR17	0.1447	0.9993	-0.9947
TR18	0.1416	0.9993	-0.9950
TR19	0.1132	0.9998	-0.9980
TR20	0.1404	0.9995	-0.9957
TR21	0.1660	0.9996	-0.9942
TR22	0.0862	0.9999	-0.9990
TR23	0.1238	0.9998	-0.9975
TR24	0.1280	0.9998	-0.9974

At the end of the first stage of the fermatean fuzzy QFD methodology, the results indicate that “Hardware infrastructure (TR1)” is the most appropriate expectation followed by “3D models and environments (TR7)”. Similarly, “High-speed communication and networks (TR3)” is obtained as the third-ranked expectation.

Table 5.12: Relationship matrix between TRs and main digital technologies

	Digital Technologies (DTs)					
TRs	DT1	DT2	DT3	DT4	DT5	DT6
TR1	AH	MH	H	VH	MH	A
TR2	VH	MH	L			
TR3	AH		H			
TR4	AH	AH			AL	
TR5	MH			VH	VH	VH
TR6	VH		VH	AH	VH	AH
TR7	VH		VH	AH	AH	AH
TR8	VH	H				
TR9	H	A	AH			
TR10	AH					
TR11	MH		MH	AH	AH	
TR12	H	VH	ML	VL	H	
TR13	MH	H		AL		A
TR14	H					
TR15	VH			VH	H	VH
TR16	AH			AH	VH	AH
TR17	AH			AH	AH	AH
TR18	VH			VH	AH	VH
TR19	VH				VH	
TR20	AH			VH	MH	AH
TR21	AH					
TR22	A			AH	H	VH
TR23	MH			VH	A	MH
TR24	ML				H	H

Thirdly, after the first stage of QFD methodology was completed, the same steps are applied for the evaluation of the main digital technologies as the second stage of QFD methodology. Primarily, the relationship matrix between TRs and main digital technologies is created by experts with linguistic expressions as in Table 5.12.

These expressions in Table 5.12 are converted to FFS. Then, the weighted fermatean fuzzy matrix is computed as in Table 5.13.



Table 5.13: Weighted fermatean fuzzy matrix for main digital technologies

	DT1		DT2		DT3		DT4		DT5		DT6	
TR1	1.074	-0.211	-1.191	-0.778	-2.105	-0.584	1.207	-0.442	-1.191	-0.778	-0.677	-1.155
TR2	1.169	-0.419	-1.385	-0.726	-0.418	1.387						
TR3	1.064	-0.202			3.099	-0.553						
TR4	1.063	-0.201	1.063	-0.201					-0.201	1.062		
TR5	-1.382	-0.726					1.169	-0.420	1.169	-0.420	1.169	-0.420
TR6	1.169	-0.419			1.169	-0.419	1.063	-0.201	1.169	-0.419	1.063	-0.201
TR7	1.180	-0.427			1.180	-0.427	1.066	-0.205	1.066	-0.205	1.066	-0.205
TR8	1.170	-0.420	2.974	-0.552								
TR9	2.840	-0.551	-0.723	-1.032	1.063	-0.201						
TR10	1.063	-0.202										
TR11	-1.385	-0.726			-1.385	-0.726	1.063	-0.201	1.063	-0.201		
TR12	2.967	-0.552	1.170	-0.420	-0.548	2.624	-0.305	1.166	2.967	-0.552		
TR13	-1.386	-0.726	2.847	-0.551			-0.201	1.062			-0.723	-1.033
TR14	2.882	-0.551										
TR15	1.169	-0.419					1.169	-0.419	2.864	-0.551	1.169	-0.419
TR16	1.063	-0.201					1.063	-0.201	1.168	-0.419	1.063	-0.201
TR17	1.063	-0.201					1.063	-0.201	1.063	-0.201	1.063	-0.201

Table 5.13: Weighted fermatean fuzzy matrix for main digital technologies (*continue*)

	DT1		DT2		DT3		DT4		DT5		DT6	
TR18	1.169	-0.419					1.169	-0.419	1.063	-0.201	1.169	-0.419
TR19	1.168	-0.419							1.168	-0.419		
TR20	1.063	-0.201					1.169	-0.419	-1.385	-0.726	1.063	-0.201
TR21	1.063	-0.201										
TR22	-0.724	-1.031					1.063	-0.201	2.792	-0.551	1.168	-0.419
TR23	-1.388	-0.725					1.168	-0.419	-0.724	-1.032	-1.388	-0.725
TR24	-0.550	2.726							2.824	-0.551	2.824	-0.551

Then, these values are aggregated with FFDWPM operator defined in (3.2.6). The obtained comprehensive assessment values and score values are shown in Table 5.14.

Table 5.14: Comprehensive assessment values and score values for main digital technologies

Main digital technologies	Comprehensive assessment values		Score values	Ranking
DT1	1.2414	-0.0967	1.9143	6
DT2	1.4446	-0.1843	3.0208	1
DT3	1.4243	-0.1808	2.8952	2
DT4	1.2708	-0.1068	2.0533	5
DT5	1.2944	-0.1198	2.1706	3
DT6	1.2885	-0.1136	2.1407	4

According to the results, as seen in Figure 5.11, the most appropriate technology supporting metaverse-based education is Blockchain (DT2). It is followed by the IoT (DT3) and AI Technology (DT5).

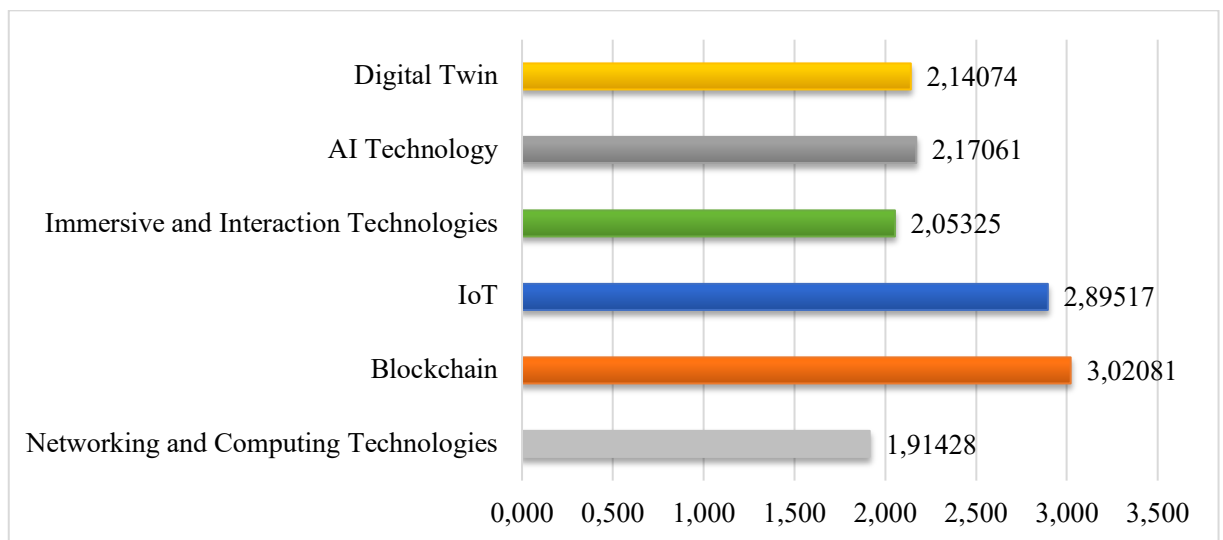


Figure 5.11: Importance degrees of the main digital technologies

5.4. Obtained Results and Discussion

Metaverse is an environment for sustainable education, independent of time and space constraints, with the potential to turn imagination into reality with the combination of advanced technologies supported by AI. The most obvious benefit of the Metaverse world in education is that it may create an immersive and engaging teaching space for professors and students by addressing their teaching and learning needs in both the real and virtual worlds.

In this context, this thesis proposed an evaluation model that consists of URs and TRs for the assessment of main digital technologies for metaverse-based education. In the first phase, academic studies in the literature and industrial reports about this subject were examined, and the opinions of experts and academicians were collected. At the end of this phase, the proposed evaluation model, which consists of URs, TRs, and main digital technologies was determined.

In the second phase, the integrated analytic approach is proposed. Firstly, the importance degrees of URs were computed with the fermatean fuzzy AHP method. According to the obtained results, the three most appropriate URs were ranked as “rapid and free access (UR23)”, “access to information resources (UR25)”, and “synchronous and live (UR24)”. These URs are the points to be considered to increase the effectiveness of metaverse-based education and to achieve efficient results. One of the main features of metaverse-based education is that it is accessible to everyone. At this point, it is very critical that access is fast and free. However, all educational resources should be accessible to everyone. The fact that education is carried out synchronously and lively in the Metaverse environment is one of the factors that increase the quality of education.

Secondly, the relationships between URs and TRs were established and the importance degrees of TRs were calculated with the HoQ approach with aggregation operators. Then, the same steps were applied and the relationships between TRs and main digital technologies were determined. Finally, the importance degrees of main digital

technologies for metaverse-based education are obtained with the proposed analytical approach. In this context, blockchain was found to be the technology that should most support metaverse-based education. Metaverse is the realization of virtual reality and augmented reality projects using the blockchain system. The digital assets acquired in this universe are recorded with the blockchain system. In this way, the digital assets of everyone who uses the Metaverse are protected and made unique.

This integrated evaluation methodology can assist researchers in assessing the potential of metaverse-based education and making more informed judgments. This thesis may be used by stakeholders in metaverse-based education as a decision support system tool for making early decisions during the development of digital technologies for metaverse-based education.

In this context, various analyzes such as sensitivity and consistency analysis of the fermatean fuzzy AHP method have been applied to show that the techniques are robust. Sensitivity analysis is an essential instrument for many decision-making problems. By altering the criteria weights, this analysis is used to evaluate the stability of the calculated optimal solution. The criteria weights are changed one at a time from 0 to 0.5 by 0.1 to implement sensitivity analysis, while the other criteria weights are maintained correspondingly. For user-based (UR1), technology-based (UR2), system-based (UR3), and organizational-based (UR4), respectively, Figure 5.12 shows the outcomes of the sensitivity analysis.

Results confirm that the weight of URs are crucial in determining the priority of ranking of the main digital technologies. Therefore, the sensitivity analysis verifies that the rankings among the main digital technologies are highly sensitive to the weight of URs in the developed approach. As can be seen from Figure 5.12, despite of fluctuations in the sequence of the main digital technologies' ranking with the changes in URs' weights, the most suitable digital technology (i.e. DT2) remains the same.

In addition, consistency analysis is an essential instrument for AHP method. For each dimension, randomly derived random consistency indexes are defined. In this thesis, an

application was made using Saaty's (1980) RI values. In the consistency analysis, RI values proposed by different authors (i.e. Crawford (1987), Golden (1989), Takeda (1993)) are applied. Then, the consistency of our evaluation matrices are tested for these RI values. Table 5.15 shows these RI values and calculated CR values for each evaluation matrix.

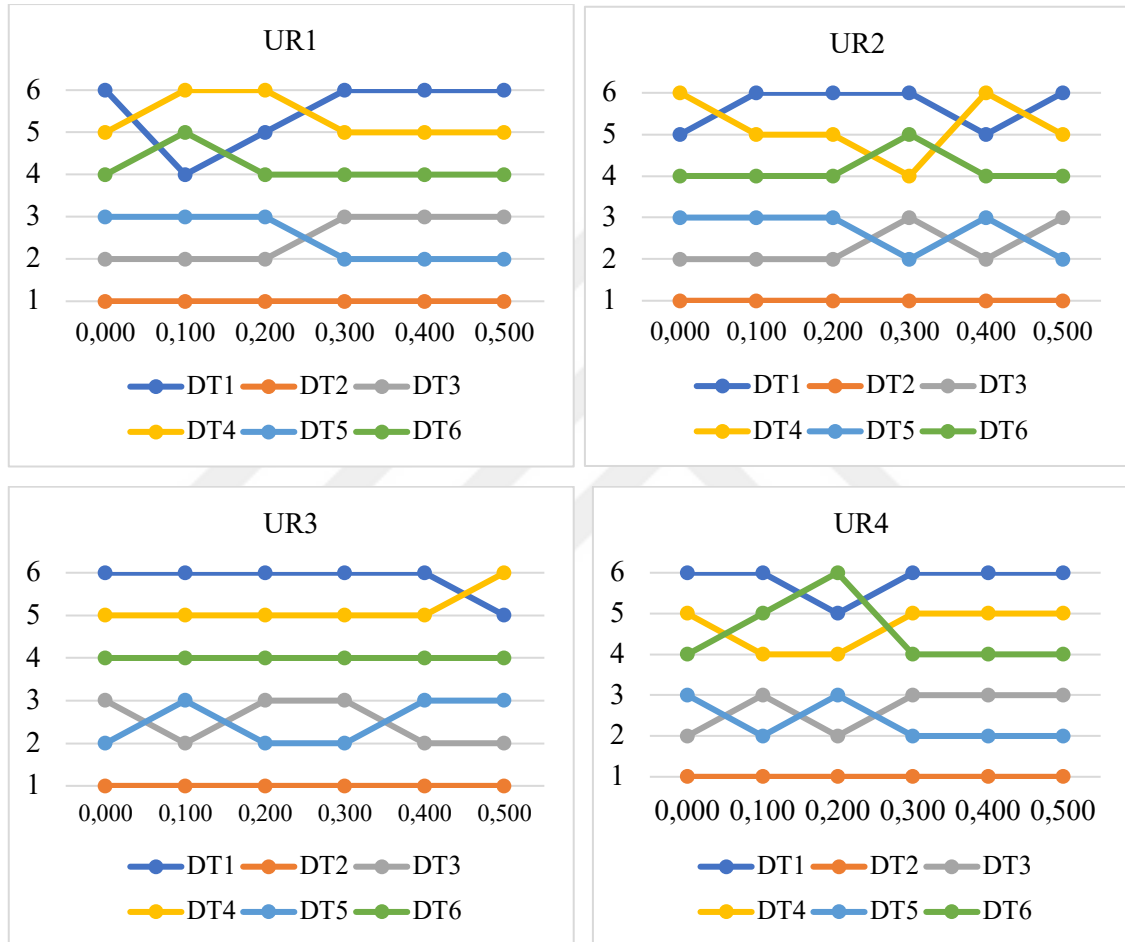


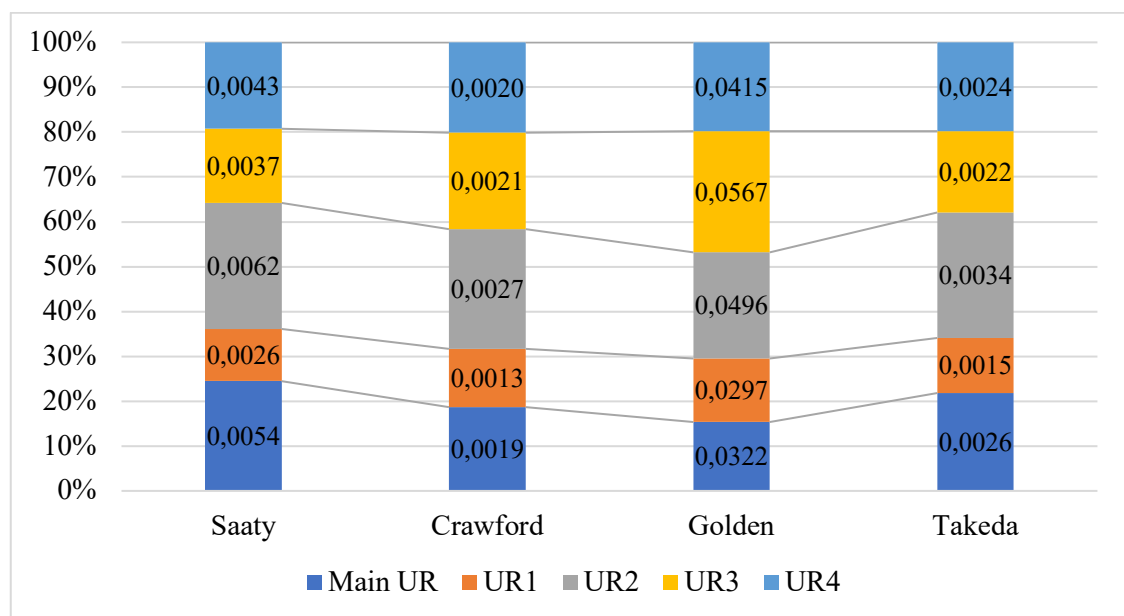
Figure 5.12: Sensitivity analysis on effects of weights of URs on DTs rankings

Among these methods, the methods proposed by Saaty (1980) and Crawford (1987) improve the consistency ratio by defining random indexes. These consistency ratios, evaluated at a threshold of 0.1, allow decision-makers to evaluate pairwise comparison matrices more easily and quickly. Takeda (1993) consistency equation is evaluated on the basis of transitivity in pairwise comparisons. However, it is not clear how much consistency an approximation to zero in the Golden (1989) consistency index indicates.

Table 5.15: RI and CR values calculated by different authors

	Saaty		Crawford		Golden		Takeda	
	RI Values	CR Values	RI Values	CR Values	RI Values	CR Values	RI Values	CR Values
Main UR	0.90	0.0054	2.629	0.0019	0.152	0.0322	1.867	0.0026
UR1	1.32	0.0026	2.628	0.0013	0.115	0.0297	2.319	0.0015
UR2	1.12	0.0062	2.626	0.0027	0.141	0.0496	2.082	0.0034
UR3	1.45	0.0037	2.484	0.0021	0.094	0.0567	2.444	0.0022
UR4	1.24	0.0043	2.642	0.0020	0.128	0.0415	2.230	0.0024

For the evaluation of the main criteria, the CR values are close to each other except for one. In Saaty's consistency scale, the calculated CR value is 0.0054 while in Crawford's consistency scale, the calculated CR value is 0.0019, while in Golden's consistency scale, the calculated CR value is 0.0322 and in Takeda's consistency scale, the calculated CR value is 0.0026. The reason for the high CR value in Golden's scale is the difference consistency scale. The CR values of all criteria calculated with all scales are shown in Figure 5.13. In this figure, it is possible to see how the criteria are distributed proportionally in each scale.

**Figure 5.13:** CR values of all URs with all scales

6. PROPOSED NEW INDEX-BASED EVALUATION APPROACH FOR TRUSTWORTHY DIGITAL EDUCATION SYSTEM

Reliability is one of the most important issues since digital technologies are used in the designed or existing digital education system. In this section, a model is proposed to ensure that the system is trustworthy, and based on this model, the trustworthiness of the system is measured. The proposed approach consists of an trustworthy digital education evaluation model and the validation of the proposed model using DETI approach with fermatean fuzzy PIPRECIA. This section contains four main sections as follows: literature review of trustworthiness in digital education, proposed trustworthy digital education evaluation model, application of the proposed approach to a real case in a digital education system, and obtained results. Details concerning these sections are presented below.

6.1. Literature Review of Trustworthiness in Digital Education System

Digital education is one of the approaches that makes education accessible anywhere and anytime with the help of digital technologies, provides equal opportunities in education and improves the quality of education in today's world. It has the potential to solve many educational problems and provide great benefits. In order for digital education to realize its full potential, trust must be established in it (Kloos et al., 2022). Trustworthiness is needed for the development, implementation and use of digital education systems. For this purpose, in this study, various definitions of trustworthy digital education have been made and various components for trustworthiness have been adopted (Lee et al., 2022; Liu et al., 2022).

To be trustworthy, digital technologies should appropriately reflect characteristics such as accuracy, explainability, interpretability, privacy, reliability, trustworthiness,

robustness, security and resilience to attacks, and ensure that bias is reduced. Factors such as fairness and transparency should be taken into account, especially during distribution or use. In addition, developing and utilizing an approach to digital education supported by digital technologies in ways that are ethical, reduce bias, promote fairness and protect privacy is essential to have a positive impact on society (Shneiderman, 2020; Rafaiani et al., 2023).

Advancing credible digital education requires a multi-pronged approach, including R&D investments addressing key technical challenges, developing metrics, standards and assessment tools to measure and evaluate the credibility of digital education, participation in the development of technical standards, public and private sectors, and preparing a diverse and inclusive workforce for the jobs of the future (Miguel et al., 2016; Surahman & Wang, 2022).

In this chapter, the education evaluation index is applied in the field of trustworthiness. The DETI is integrated with the fermatean fuzzy PIPRECIA method. In this context, in this thesis, the main components that will ensure that the digital education system is trustworthy are identified and an evaluation model is created. Based on this evaluation model, the trustworthiness index for a digital education system is calculated.

6.2. Proposition of Trustworthy Digital Education Evaluation Model with Index-based Evaluation Approach

In this chapter, the proposed research methodology is illustrated in Figure 6.1. In this methodology, there are three parts: the model proposition, fermatean fuzzy PIPRECIA, and DETI. First of all, the evaluation components are determined by examining academic papers, industrial reports, and experts' opinions. Then, the weights of these components are calculated with fermatean fuzzy PIPRECIA method. Finally, the digital education trustworthiness index is computed for the digital education system and action plans are proposed according to the results.

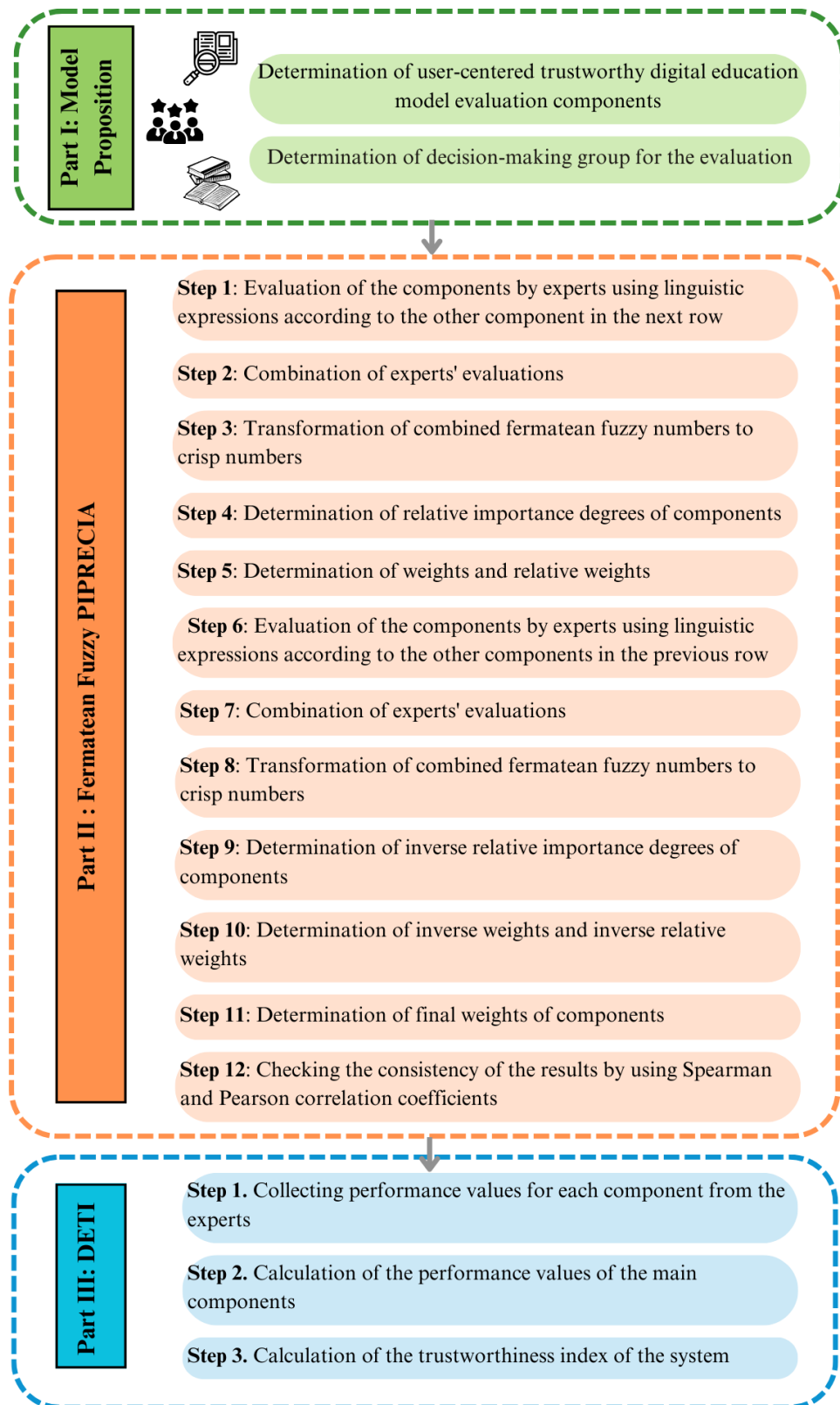


Figure 6.1: Flowchart of the proposed index-based evaluation approach for trustworthy digital education system

6.2.1. Components of Trustworthy Digital Education Evaluation Model

The digital transformation journey with the concept of Industry 4.0 is an approach that companies of all sizes and sectors should adopt in a competitive environment. Based on this approach, this thesis section presents a trustworthiness journey of the digital education system. This journey aims to improve the trustworthiness level of digital education systems. Within the scope of this journey, a trustworthiness model should first be created, followed by a trustworthiness assessment, and finally, a trustworthiness roadmap should be created.

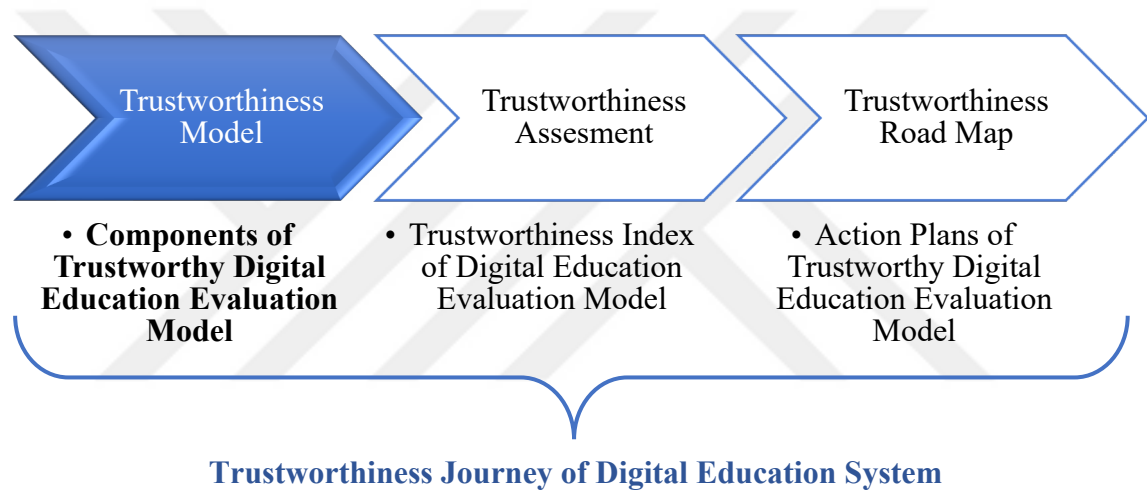


Figure 6.2: Trustworthiness journey of digital education system-phase I

In the first phase of this journey, the components of the trustworthy digital education evaluation model are identified (Figure 6.2). These components are shown in Table 6.1. These components and their explanations are as follows:

- *User agency and oversight:* Placing humans at the center means shifting from mimicking to empowering individuals. Instead than attempting to imitate or replace human stakeholders (teachers, learners, etc.), the objective is to create tool-like user interfaces that boost their skills to accomplish the tasks themselves (thereby retaining their agency and control over the learning setting) (Seldon et al., 2020; Kloos et al., 2022; Liu et al., 2022).

- *Perception of ethics:* An individual's ethical perception is an individual's ethical judgment about the extent to which he or she finds an issue or behavior ethically important. Ethical perception, which can be expressed as a person's perception of being aware of a moral issue in a digital system, acts as a catalyst in the moral decision-making process (Medeiros et al., 2017; Eismann et al., 2022; Kieslich et al., 2022).
- *Ethical decision making:* Digital education systems should support human autonomy and decision-making. Ethical decision-making is systematic thinking when there are conflicting alternatives and choosing the one that is most morally reasonable and most compatible with ethical principles. Compliance with the principles of right, justice, equity, and honesty is important in ethical decision-making (Shneiderman, 2020; Qin et al., 2020).
- *Privacy and data governance:* Privacy and data governance must be guaranteed throughout the lifespan of a digital education system. This covers both the information supplied by the user and the information created about the user as a result of their engagement with the system. Digital recordings of human behavior may enable digital education systems to infer not just preferences but also sexual orientation, age, gender, religion or political beliefs. To earn individuals' trust in the data-collection process, it must be assured that the information gathered about them will not be used to unlawfully or unfairly discriminate against them (AI HLEG, 2019; Seldon et al., 2020).
- *Protection of human rights and intellectual property rights:* Human rights are a concept of public law that took shape at a particular historical moment in response to known world events and the aggravation of international relations. With the proliferation of digital technologies, new ethical questions arise regarding the implementation of fundamental human rights, such as respect for privacy, freedom of expression, prohibition of discrimination, and protection of vulnerable groups. The existing digital system should be modeled under the law with these rights in mind (Todd et al., 2017; Kim & Park, 2022; Eismann et al., 2022).
- *Codes of conduct:* Stakeholders can sign up for the guidelines and adjust their corporate responsibility charter, key performance indicators, codes of conduct, or internal policy papers to contribute to the goal of trustworthy digital education. In

general, an institution dealing with digital education systems can declare its aims and underpin them with standards of desired values such as basic rights, transparency, and harm avoidance (AI HLEG, 2019; Rafaiani et al., 2023).

- *Societal and environmental well-being*: The larger society, other sentient creatures, and the environment should all be considered stakeholders throughout the life cycle of the digital education system. The sustainability and ecological responsibility of digital education systems should be supported, and research into digital education systems addressing global concerns, such as the Sustainable Development Goals, should be encouraged (Seldon et al., 2020). It includes sustainability and environmental friendliness, social impact, society, and democracy (AI HLEG, 2019; Liu et al., 2022; Kieslich et al., 2022).
- *Harmony and user-friendliness*: A friendly digital education system is a system that has been designed to be safe and beneficial for humans. The human-friendliness of the system improves the quality of educational outcomes. A human-friendly system must first appeal to the user as an interface. The user's adaptation to the system is one of the other factors that increase the quality of education (Liu et al., 2022; Kloos et al., 2022).
- *Data integrity and quality*: Data integrity is the protection and assurance of the accuracy and consistency of data throughout its entire life cycle. It includes the processes of ensuring the validity and accuracy of data and protecting data. It is a critical element for the design, implementation and use of any digital education system that stores, retrieves or processes data. The integrity of your data within a database should be ensured at the design stage through the use of standardized rules and procedures (Todd et al., 2017; Kieslich et al., 2022).
- *Cultural integrity*: The practice of respecting and recognizing the ownership of resources, customs, and information that derive from a certain culture, community, or system is known as cultural integrity. Even though the existing education system is being digitized, the cultural integrity of the system should be preserved and the elements that are part of that culture should be emphasized (Watts et al., 2017; Remian, 2019; Rafaiani et al., 2023).
- *Empowering responsible participation*: Participation for empowerment is defined as a guide to help users adopt approaches and attitudes that promote community

empowerment in their day-to-day educational activities. It is not designed for users to reproduce the training with community groups, but rather for them to use the concepts and skills on their own (Liu et al., 2022; Kloos et al., 2022; Lee et al., 2022).

- *Network security:* Network security is a broad concept that encompasses a wide range of technology, equipment, and operations. It is a collection of rules and settings that use both software and hardware to safeguard the integrity, confidentiality, and accessibility of computer networks and data. It guards against unwanted access, abuse, or theft of the underlying networking infrastructure. It entails building a secure infrastructure on which devices, applications, users, and applications may operate safely (Shneiderman, 2020; Rafaiani et al., 2023).
- *Individual awareness:* Individual awareness is the ability to look within and recognize oneself as an individual, apart from the surroundings and other people. According to self-awareness theory, when a person concentrates on himself/herself, he/she compares and analyzes his/her actions against his/her internal norms and ideals. Users should be aware that they represent themselves as individuals in the digital system they are in (Todd et al., 2017; Kusumaningrum et al., 2019).
- *Personal responsibility:* Personal responsibility is both a recognition of the importance of the standards society sets for individual behavior and a willingness to make a concentrated personal effort to live up to those standards. By taking personal responsibility for their education, individuals recognize that they are responsible for their own learning and growth. It is not enough to simply attend classes or complete assignments; it is necessary to actively participate in the learning process, take initiative and seek new opportunities to learn (Todd et al., 2017; Liu et al., 2022).
- *Identity controllability:* Identity controllability refers to the methods and technologies that are used to manage and safeguard user identities inside a digital system. It has a wide range of features like as user provisioning, role-based access control, password management, and auditing. Users should be able to use a pseudonym instead of their real name when using the service (Liu et al., 2022; Kieslich et al., 2022).
- *Open and collaborative:* An open system is one with external interactions. Depending on the field that defines the notion, such interactions can take the form

of information, energy, or material transfers into or out of the system border. A collaboration system enables individuals to communicate and exchange documents in a digital world by utilizing software and technology (Todd et al., 2017; Liu et al., 2022).

- *Social responsibility*: Social responsibility is the ethical framework within which a company or individual behaves in the best interests of society as a whole as well as in its own. Social responsibility is a type of obligation that each individual does to keep the economy and the environment in balance. It is a method of attaining long-term viability. Adopting essential social responsibility concepts like accountability and transparency may assist any company or institution in securing its long-term survival and success (Todd et al., 2017; Watts et al., 2017; Qin et al., 2020).
- *Data protection*: Data protection is the process of protecting sensitive information against damage, loss, or corruption. To protect users' private data from exploitation and to prevent cyber-attacks, effective security measures are required. As the amount of data created and stored increases, data protection is becoming increasingly important. Legal regulations have been introduced to reveal the positive aspects of the digitalized world and to protect against its negative aspects. Measures have been taken to protect data such as IT law, cyber security, and the Law on the Protection of Personal Data (Eismann et al., 2022; Ooi et al., 2023).
- *Verifiability*: Verifiability indicates that the program is planned, built, and tested in such a way that its intended specifications can be verified. System verification is a collection of operations used to validate any element, such as a system, document, service, task, or need. These activities are planned and carried out during the system's life cycle. In general, system verification refers to the application of test cases produced from system requirements to an integrated system (Remian, 2019; Shneiderman, 2020; Liu et al., 2022).
- *Information credibility*: The capacity of a system to be trusted in sending and completing transactions is characterized by its credibility. communication credibility is a critical determinant of communication efficacy and is defined as the recipient's assessment of the message's legitimacy. In the digital setting, information credibility is regarded as crucial since the positive nature of the information enhances the recipient's reception of the information. Users may now create more

material on digital education systems and platforms because of advancements in online communication technologies (Sadaa et al., 2022; Rafaiani et al., 2023).

- *Institutional compliance:* Activities that enable the coordination, management, and monitoring of risks connected with federal, state, and local laws and regulations are categorized as institutional compliance. It addresses corporate rules and processes as well as federal and state legislation. Enforcing compliance assists your institution in preventing and detecting rule infractions, safeguarding it from penalties and litigation (Watts et al., 2017; Qin et al., 2020; Shneiderman, 2020).
- *Transparency:* This concept includes transparent decision-making procedures of education systems and publicly available ethical policies of institutions. When determining the trustworthiness of the user-centered digital education system, transparency is crucial to ensure that the processes performed are under the specification. The trustworthiness of the user-centered digital education system must be transparent so that it can be verified according to ethical requirements (Aydemir & Dalpiaz, 2018; Seldon et al., 2020; Kloos et al., 2022).
- *Technical robustness and safety:* Digital education systems should avoid unexpected and unacceptable harm. It includes resilience to attack and security, a fallback plan and general safety, accuracy, reliability, and reproducibility (AI HLEG, 2019). Technical robustness and safety are defined as digital education systems that are secure and resistant to attack, have a backup plan in case of failures, are sufficiently accurate, and can provide dependable and repeatable outcomes (Seldon et al., 2020; Liu et al., 2022).
- *Traceability:* The data sets and procedures that result in the digital education system's decisions, including data collection and labeling, as well as the algorithms utilized, should be documented to the highest degree feasible to enable for traceability and increased transparency. This also applies to the digital education system's judgments. This allows for the discovery of the reasons why an AI judgment was incorrect, which may aid in the prevention of future errors. Traceability makes auditability and explainability easier (AI HLEG, 2019; Rafaiani et al., 2023).
- *Fairness and justice:* For an education system to be trustworthy, it is crucial that it is fair. Giving each individual what he or she deserves, or, in more conventional

terms, giving each person his or her due, is what justice entails. While justice typically refers to a standard of rightness, fairness frequently refers to the ability to judge without regard for one's feelings or interests; fairness has also been used to refer to the ability to make judgments that are concrete and specific to a particular case (Liu et al., 2022; Kim & Park, 2022).

- *Diversity inclusion and non-discrimination:* This concept refers to the inclusion of users regardless of gender, race and age distribution. All human beings must be treated with equal moral value and dignity. This goes beyond non-discrimination, which allows for objectively justified disparities between dissimilar situations. In the context of digital education, equality means that the system's processes cannot provide unfairly skewed outcomes. This also necessitates proper consideration for potentially vulnerable individuals and groups, such as workers, women, people with disabilities, ethnic minorities, children, consumers, and others who may face exclusion (AI HLEG, 2019; Seldon et al., 2020).
- *Democratic participation:* Democratic involvement refers to actions designed to affect the conduct of persons with decision-making authority. In a culture where participation is valued, being unable to engage is a terrible deprivation. Everyone has equal rights in the system and the system must be democratically mature (Liu et al., 2022; Kloos et al., 2022).
- *Moral judgment and maturity:* Moral judgment is the assessment of a certain conduct as good or evil, right or wrong. Moral maturity is characterized by the depth and consistency of moral judgment; the knowledge that any moral judgment may be faulty; and the recognition that moral judgment is complicated, in that moral principles may need to be understood if they are to be applied to a given instance (Todd et al., 2017; Kim & Park, 2022).
- *Transparent privacy standards:* All elements of digital education, including data, systems, and business models should be explainable. Under transparent confidentiality standards, information on the activities of public institutions is created and made publicly available, with limited exceptions, immediately and in open data formats without restrictions on reuse. For the existing education system to be credible, it must comply with these standards (Shneiderman, 2020; Rafaiani et al., 2023).

- *Auditability*: Auditability requires enabling the evaluation of algorithms, data, and design processes. This does not imply that information on digital education business models and intellectual property must always be freely available. Internal and external audits, as well as the availability of such evaluation reports, can contribute to the technology's credibility. Digital education systems should be auditable independently in applications impacting basic rights, particularly safety-critical applications (AI HLEG, 2019; Seldon et al., 2020).



Table 6.1: Trustworthy digital education evaluation model

First-level components	Second-level components	References
Ethical (C1)	User agency and oversight (C11)	Todd et al., 2017; Liu et al., 2022; Kim & Park, 2022; Kloos et al., 2022; Rafaiani et al., 2023
	Perception of ethics (C12)	Medeiros et al., 2017; Sadaa et al., 2022; Eismann et al., 2022; Kieslich et al., 2022
	Ethical decision making (C13)	Medeiros et al., 2017; Shneiderman, 2020; Qin et al., 2020
	Privacy and data governance (C14)	Shneiderman, 2020; Rafaiani et al., 2023
	Protection of human rights and intellectual property rights (C15)	Todd et al., 2017; Kim & Park, 2022; Eismann et al., 2022; Lee et al., 2022
	Codes of conduct (C16)	Todd et al., 2017; Kloos et al., 2022
Beneficial (C2)	Societal and environmental well-being (C21)	Qin et al., 2020; Liu et al., 2022; Rafaiani et al., 2023
	Harmony and user-friendliness (C22)	Liu et al., 2022; Kloos et al., 2022
	Data integrity and quality (C23)	Todd et al., 2017; Kieslich et al., 2022
	Cultural integrity (C24)	Watts et al., 2017; Remian, 2019; Rafaiani et al., 2023
	Empowering responsible participation (C25)	Liu et al., 2022; Kloos et al., 2022; Lee et al., 2022
	Network security (C26)	Shneiderman, 2020; Eismann et al., 2022; Kieslich et al., 2022; Rafaiani et al., 2023

Table 6.1: Trustworthy digital education evaluation model (*continue*)

First-level components	Second-level components	References
Responsible (C3)	Individual awareness (C31)	Todd et al., 2017; Kusumaningrum et al., 2019
	Personal responsibility (C32)	Todd et al., 2017; Liu et al., 2022
	Identity controllability (C33)	Liu et al., 2022; Kieslich et al., 2022
	Open and collaborative (C34)	Todd et al., 2017; Liu et al., 2022; Kieslich et al., 2022
	Social responsibility (C35)	Todd et al., 2017; Watts et al., 2017; Qin et al., 2020
	Data protection (C36)	Sadaa et al., 2022; Eismann et al., 2022; Ooi et al., 2023
Explainable (C4)	Verifiability (C41)	Remian, 2019; Shneiderman, 2020; Liu et al., 2022
	Information credibility (C42)	Sadaa et al., 2022; Kloos et al., 2022; Lee et al., 2022
	Institutional compliance (C43)	Todd et al., 2017; Watts et al., 2017; Qin et al., 2020; Shneiderman, 2020
	Transparency (C44)	Remian, 2019; Rafaiani et al., 2023
	Technical robustness and safety (C45)	Kusumaningrum et al., 2019; Shneiderman, 2020; Liu et al., 2022; Lee et al., 2022; Rafaiani et al., 2023
	Traceability (C46)	Medeiros et al., 2017; Shneiderman, 2020; Rafaiani et al., 2023

Table 6.1: Trustworthy digital education evaluation model (*continue*)

First-level components	Second-level components	References
Fair (C5)	Fairness and justice (C51)	Liu et al., 2022; Kim & Park, 2022
	Diversity inclusion and non-discrimination (C52)	Todd et al., 2017; Qin et al., 2020; Sadaa et al., 2022; Kim & Park, 2022
	Democratic participation (C53)	Liu et al., 2022; Kloos et al., 2022
	Moral judgment and maturity (C54)	Todd et al., 2017; Medeiros et al., 2017; Kim & Park, 2022
	Transparent privacy standards (C55)	Shneiderman, 2020; Liu et al., 2022; Eismann et al., 2022; Rafaiani et al., 2023
	Auditability (C56)	Todd et al., 2017; Watts et al., 2017; Sadaa et al., 2022; Eismann et al., 2022

6.2.2. Digital Education Trustworthiness Index (DETI)

A trustworthy system must meet compliance-mandated requirements for trustworthiness characteristics throughout the system's lifecycle. They are defined by laws, regulatory standards, and industry-accepted best practices that apply to digital systems. Beyond these, some organizations may set higher trustworthiness targets based on corporate vision, roadmap, market positioning, and other objectives (Swe et al., 2022; Maras et al., 2023).

In the second phase of this journey, the digital education system is evaluated with the trustworthiness index (Figure 6.3). This assessment is index-based and based on the opinions of experts.

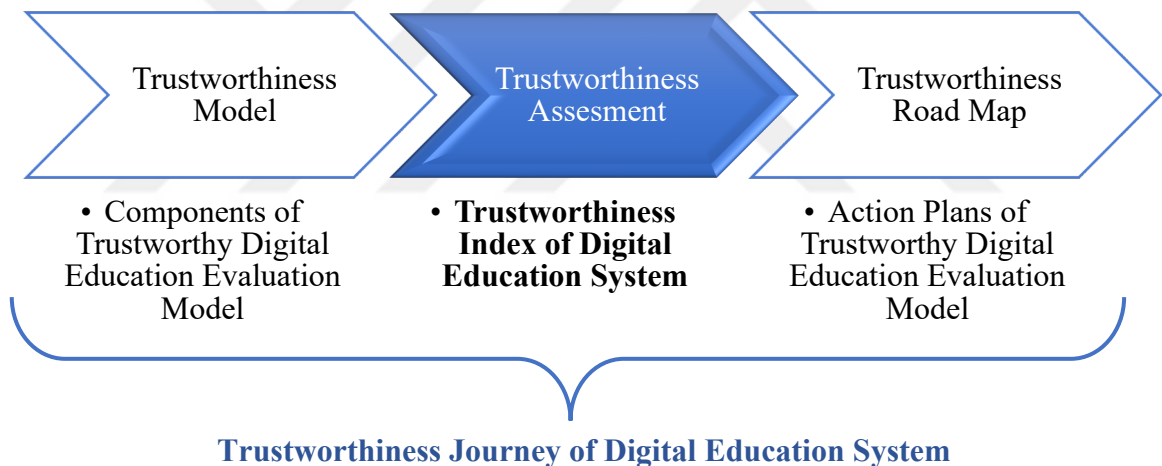


Figure 6.3: Trustworthiness journey of digital education system-phase II

DETI is a trustworthiness degree to which a digital education system is reliable against all kinds of digital threats in the world of digital education. With this index, the existing system is evaluated from the perspective of ethical, beneficial, responsible, explainable, and fair.

DETI is derived in three steps:

- assigning an index value to the identified components by experts

- multiplying the index values by the component weights
- calculation of the level of trustworthiness of digital education system

6.2.3. Action Plans of Trustworthy Digital Education Evaluation Model

In the third phase of this journey, action plans for the trustworthy digital education evaluation model are presented within the scope of the trustworthiness road map.

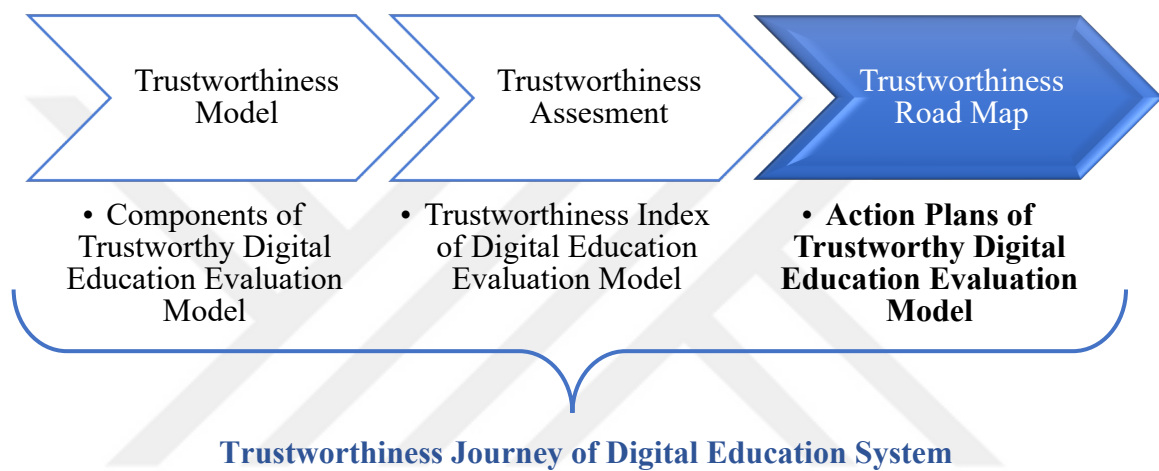


Figure 6.4: Trustworthiness journey of digital education system-phase III

Developing a shared vision for educational trustworthiness requires both building consensus on designing digital education as trustworthy and reaching a consensus on how best to realize a trustworthy education system. At this point, possible solution mechanisms are reviewed to determine which actions can make a digital education system more trustworthy. These action plans are adapted from the European Commission’s (2019) report “Ethics Guidelines for Trustworthy AI”.

In order to interpret the scores obtained as a result of the index calculation in a meaningful way and to move the system from its current point to a safer point, some action plans consisting of solution mechanisms are proposed. These action plans (Aydemir & Dalpiaz, 2018; European Commission, 2019; AI HLEG, 2019; Seldon et al., 2020; Shneiderman, 2020; Eismann et al., 2022) are as shown in Table 6.2.

Table 6.2: Action Plans

Action Plans	Actions		
Ethical Action Plan	Must-Do	Ideal	Leadership
	Implement regulations	Ensure that trustworthy digital education is part of the curriculum	Create ethics and rule of law by design (X-by-design)
	Standardize processes	Build architectures for trustworthy digital education	Certify processes
		Provide education and awareness to promote a trustworthy mindset	
Beneficial Action Plan	Must-Do	Ideal	Leadership
	Provide education and awareness to promote a trustworthy mindset	Ensure stakeholder engagement and social dialog	Monitor and report impacts of trustworthy digital education
	Standardize processes		Continuously monitor the quality of service indicators
Responsible Action Plan	Must-Do	Ideal	Leadership
	Standardize processes	Test and validate processes	Continuously monitor the quality of service indicators
	Provide education and awareness to promote a trustworthy mindset		

Table 6.2: Action Plans (*continue*)

Action Plans	Actions		
Explainable Action Plan	Must-Do	Ideal	Leadership
	Standardize processes	Test and validate processes	Ensure that trustworthy digital education is part of the curriculum
	Incorporate explanation methods into processes	Build diverse and inclusive design teams	
Fair Action Plan	Must-Do	Ideal	Leadership
	Implement regulations	Ensure stakeholder engagement and social dialog	Certify processes
	Standardize processes	Test and validate processes	Build architectures for trustworthy digital education
	Build diverse and inclusive design teams		

6.3. Application of the Proposed Approach

This section aims to illustrate the proposed approach for the trustworthiness level of the digital education system used in ABC university with an application. For this reason, the trustworthiness index of the digital education system is calculated by making evaluations by experts. In this study, there are 3 DMs, 2 academicians and 1 industry expert. Academics have been working on subjects such as engineering ethics and informatics ethics for more than 5 years. The industrial expert owns his own cyber security company and has been working on these issues for years. In this case study, the Delphi method is used to create a consensus structure. The Delphi method is used to manage the relationships between the DMs and is similar to the DMs' foresight process (Hsu & Sandfors, 2007). This method gathers data from a panel of well selected DMs because information collected from a panel is considered to be more credible than that obtained from a single DM (Hsu et al., 2010).

In the first part of the study, an evaluation model is created as in Figure 6.5. The components in this evaluation model are evaluated pairwise by the experts using the scale in Table 3.6 and the importance levels of the components are determined.

DMs are asked to give a coefficient greater than 1 if a criterion is considered more important than the previous criterion, 1 if it is considered at the same level of importance, and a coefficient less than 1 if it is considered less important. In this way, equation (3.4.28) is used to find the relative importance values for each DM. The relative importance values of the main components are shown in Table 6.3.

Table 6.3: Relative importance values of the main components

	DM1		DM2		DM3	
C1	-	-	-	-	-	-
C2	0.50	0.80	0.40	0.85	0.40	0.85
C3	0.80	0.50	0.75	0.60	0.60	0.70
C4	0.40	0.85	0.60	0.70	0.80	0.50
C5	0.80	0.50	0.75	0.60	0.75	0.60

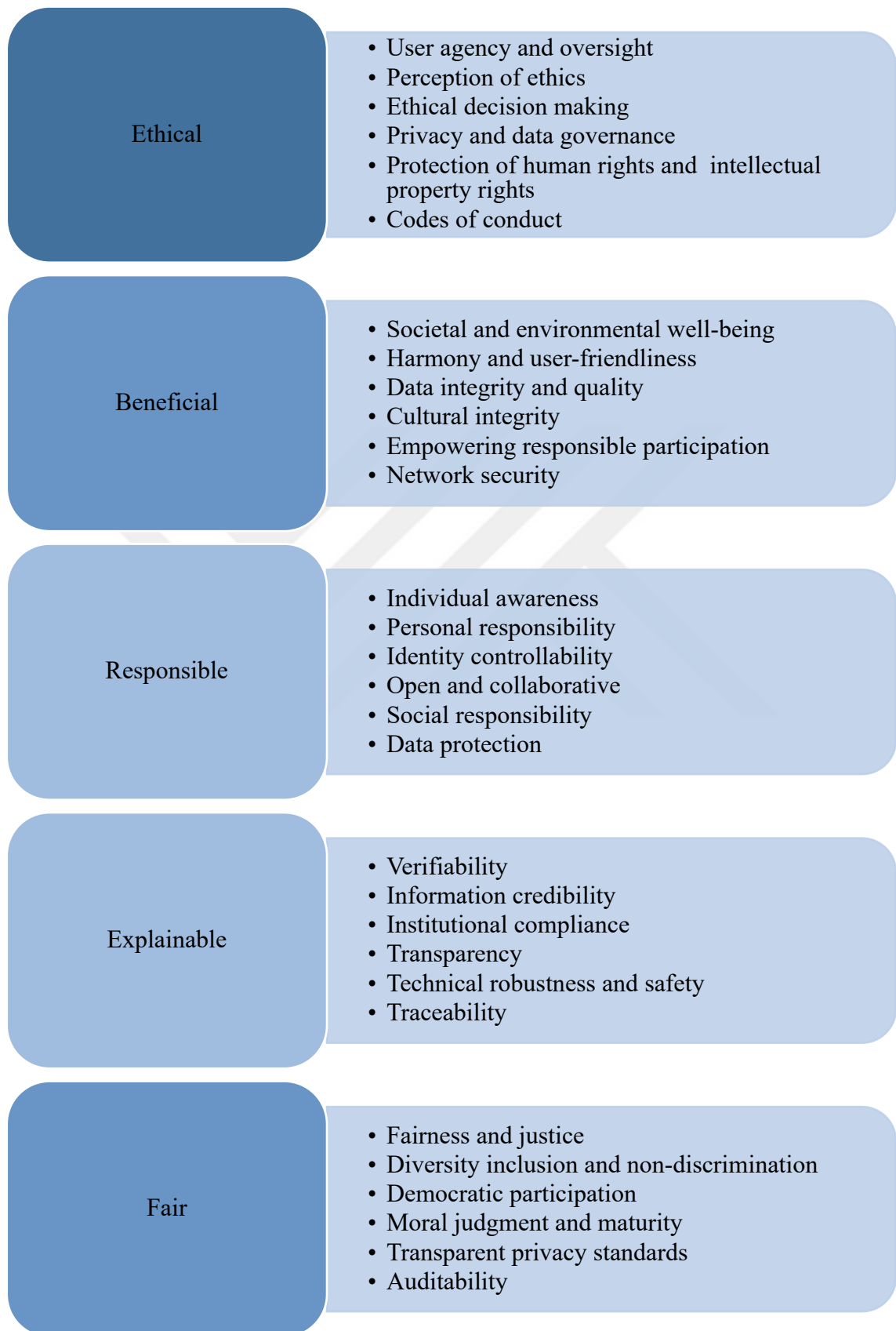


Figure 6.5: Trustworthy digital education evaluation model

By taking the geometric mean of these fermatean fuzzy numbers, the evaluations of three separate experts are brought together. These fermatean fuzzy numbers are defuzzified with equation (3.4.29) and the s_j matrix is formed. Then, coefficient k_j , weight q_j , and relative weights w_j are calculated with equations (3.4.30)-(3.4.32). These values are shown in Table 6.4.

Table 6.4: Results of PIPRECIA method for the main components

	s_j		k_j	q_j	w_j
C1	-	-	1.000	1.000	0.176
C2	0.431	1.220	0.728	1.374	0.242
C3	0.711	0.678	1.118	1.229	0.216
C4	0.577	1.114	1.168	1.052	0.185
C5	0.766	0.617	1.029	1.022	0.180

After that, Inverse PIPRECIA process is performed. Firstly, the DMs carried out the aforementioned evaluation from the end to the beginning. This time, the DMs are asked to give a coefficient greater than 1 if they considered any criterion more important than the next criterion; 1 if they considered it at the same level of importance; and a coefficient less than 1 if they considered it less important. In this way, equation (3.4.33) is used to find the inverse relative importance values for each DM. The inverse relative importance values of the main components are shown in Table 6.5.

Table 6.5: Inverse relative importance values of the main components

	DM1		DM2		DM3	
C1	0.95	0.20	0.90	0.40	0.90	0.40
C2	0.80	0.50	0.75	0.60	0.80	0.50
C3	0.75	0.60	0.60	0.70	0.60	0.70
C4	0.40	0.85	0.50	0.80	0.75	0.60
C5	-	-	-	-	-	-

By taking the geometric mean of these fermatean fuzzy numbers, the evaluations of three separate experts are brought together. These fermatean fuzzy numbers are

defuzzified with equation (3.4.29) and the s_j' matrix is formed. Then, coefficient k_j' , inverse weight q_j' , and inverse relative weights w_j' are calculated with equations (3.4.34)-(3.4.36). These values are shown in Table 6.6.

Table 6.6: Results of Inverse PIPRECIA method for the main components

	s_j'		k_j'	q_j'	w_j'
C1	0.916	0.362	0.723	1.203	0.241
C2	0.783	0.572	0.997	0.870	0.174
C3	0.646	0.795	1.219	0.867	0.174
C4	0.531	1.182	0.946	1.057	0.212
C5	-	-	1	1.000	0.200

The consistency of the results obtained from the PIPRECIA and reverse PIPRECIA method is checked using Spearman and Pearson correlation coefficients.

Finally, the final weights of the main components is calculated with (3.4.37). These steps are applied for all sub-components and the consistency of all these values is checked by calculating Spearman and Pearson correlation coefficients. Spearman and Pearson correlation coefficients calculated for the components are given in Table 6.7. The results are shown in Table 6.8.

Table 6.7: Spearman and Pearson correlation coefficients

	Main components	C1	C2	C3	C4	C5
Spearman CC	0.752	0.777	0.737	0.769	0.729	0.729
Pearson CC	0.943	0.866	0.648	0.646	0.320	0.740

Table 6.8: Final results

Main Components	Weights	Sub-components	Relative weights	Global weights	Rank
C1	0.2085	C11	0.2005	0.0418	2
		C12	0.1717	0.0358	10
		C13	0.1810	0.0377	7
		C14	0.1446	0.0301	21
		C15	0.1452	0.0303	19
		C16	0.1571	0.0327	16
C2	0.2080	C21	0.1302	0.0271	28
		C22	0.1458	0.0303	17
		C23	0.1588	0.0330	15
		C24	0.1851	0.0385	6
		C25	0.1853	0.0385	5
		C26	0.1948	0.0405	4
C3	0.1950	C31	0.1452	0.0283	25
		C32	0.1437	0.0280	26
		C33	0.1484	0.0289	23
		C34	0.1140	0.0222	30
		C35	0.1928	0.0376	8
		C36	0.2560	0.0499	1
C4	0.1984	C41	0.2093	0.0415	3
		C42	0.1836	0.0364	9
		C43	0.1735	0.0344	13
		C44	0.1528	0.0303	18
		C45	0.1428	0.0283	24
		C46	0.1381	0.0274	27
C5	0.1901	C51	0.1850	0.0352	12
		C52	0.1806	0.0343	14
		C53	0.1860	0.0353	11
		C54	0.1588	0.0302	20
		C55	0.1334	0.0253	29
		C56	0.1562	0.0297	22

To calculate the trustworthiness index, the existing digital education system is evaluated for each component by DMs using linguistic scale in Table 3.6. The evaluation matrix is shown in Table 6.9.

Table 6.9: Evaluation matrix

Components	Index Value	Components	Index Value	Components	Index Value
C11	VH	C21	A	C31	MH
C12	H	C22	H	C32	A
C13	H	C23	H	C33	ML
C14	MH	C24	MH	C34	MH
C15	VH	C25	MH	C35	A
C16	MH	C26	A	C36	MH
Components	Index Value	Components	Index Value		
C41	ML	C51	H		
C42	A	C52	AH		
C43	MH	C53	AH		
C44	A	C54	VH		
C45	MH	C55	MH		
C46	MH	C56	A		

Using equations (3.4.39) and (3.4.40), the DETI for the digital education system is calculated. An example of the calculation of the ethical component is as follows:

$$\begin{aligned}
 P(c_1) &= \frac{0.042 * 8 + 0.036 * 7 + 0.038 * 7 + 0.030 * 6 + 0.030 * 8 + 0.033 * 6}{(0.042 + 0.036 + 0.038 + 0.030 + 0.030 + 0.033)} \\
 &= 7.044
 \end{aligned}$$

The overall trustworthiness score of the digital education system is provided in Table 6.10.

Table 6.10: Overall score of the digital education system

Main Components	Scores
Ethical	7.044
Beneficial	5.980
Responsible	5.367
Explainable	5.245
Fair	7.446
Total Score (DETI):	31.082

6.4. Obtained Results and Discussion

A trustworthy approach is critical to enable responsible competitiveness because it provides the basis for all individuals touched by digital education systems to believe that their design, development, and usage are legal, ethical, and resilient. The DETI intends to make ethics a central pillar in the development of a distinct approach to digital education, one that wants to enrich, empower, and preserve both individual human flourishing and societal well-being.

In this context, this study proposed an evaluation model that consists of user-centered trustworthy digital education components for DETI. In the first part, academic studies in the literature and industrial reports about this subject were examined, and the opinions of experts were collected. In the second part, the importance degrees of these components were computed with the fermatean fuzzy PIPRECIA method. According to the obtained results, the three most appropriate components were ranked as “Data protection (C36)”, “User agency and oversight (C11)”, and “Verifiability (C41)”. In the last section, the trustworthiness of the digital education system was calculated by DETI using the weights obtained with the fermatean fuzzy PIPRECIA method. To better understand the current situation, the scores are visualized by the radar chart in Figure 6.6.

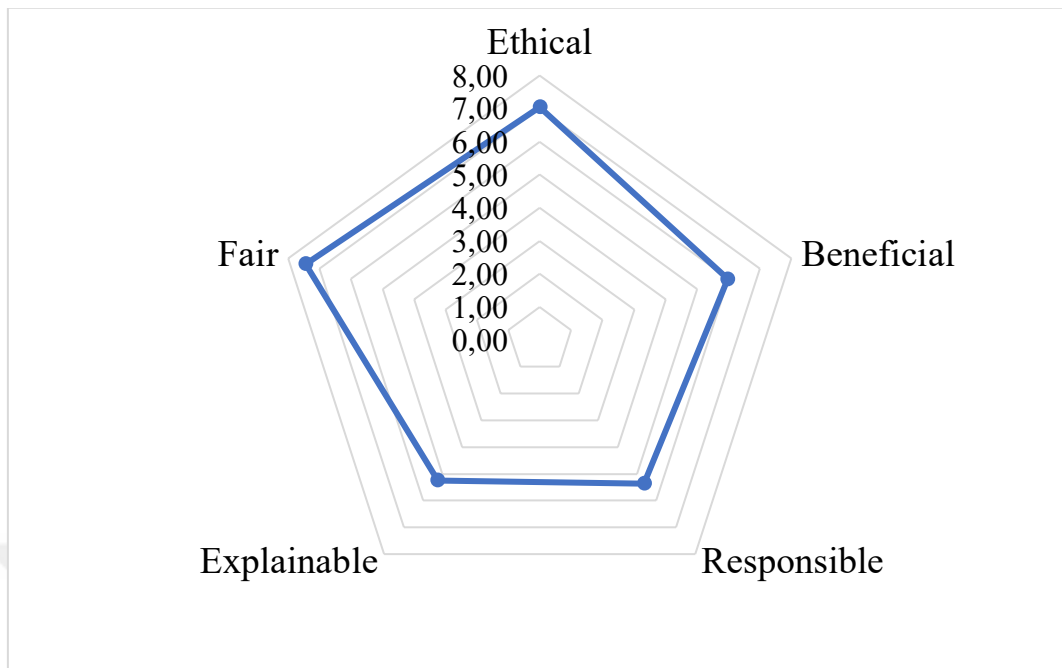


Figure 6.6: Radar chart visualizing trustworthiness of digital education system

"Fair" and "Ethical" have the highest score in the evaluated digital education system. It can be said that the other components have lower scores than these two components. "Beneficial", "Responsible", and "Explainable" have close values. Institutions and stakeholders should develop these components for the existing digital education system. For more meaningful analysis, the scores of the subcomponents are shown in Figure 6.7.

When the main component "Ethics" is analyzed, it is seen that the sub-component with the highest value is "Human agency and oversight (C11)" by far. "Perception of ethics (C12)", "Ethical decision making (C13)", and "Protection of human rights and intellectual property rights (C15)" have very close values to each other. Although "Privacy and data governance (C14)" and "Codes of conduct (C16)" have close values, they have the lowest values of this component and these two are the components that need to be developed first.

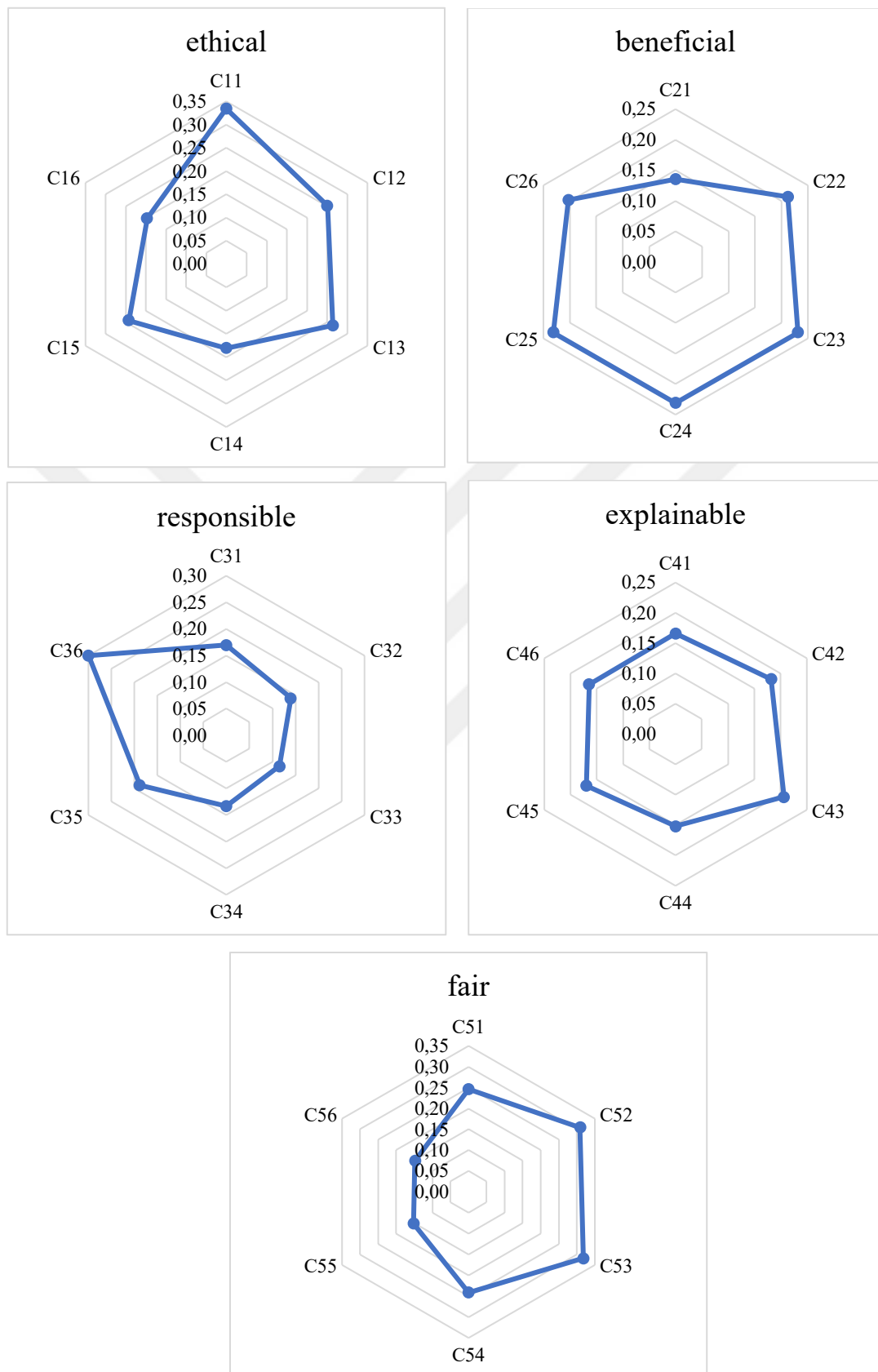


Figure 6.7: Radar chart visualizing trustworthiness of digital education system under components

In the “Beneficial” main component, “Data integrity and quality (C23)”, “Cultural integrity (C24)”, “Empowering responsible participation (C25)” have almost the same value and this component has the highest value with a value of approximately 0.231. These are followed by “Harmony and human-friendliness (C22)” and “Network security (C26)” with close values. The lowest value in this main component is “Societal and environmental well-being (C21)” with 0.135.

In the main component “Responsible”, “Data protection (C36)” is much ahead of the other subcomponents with a value of 0.300. Here, it is possible to say that all other subcomponents should be improved. In the main component “Explainable”, it is possible to say that all subcomponents have almost the same values. In the “Fair” main component, “Diversity inclusion and non-discrimination (C52)” and “Democratic participation (C53)” have very high values with 0.310, while “Transparent privacy standards (C55)” and “Auditability (C56)” have low values with 0.150.

Table 6.11: Index score and their explanation

Scores	Explanation
0 – 3.99	Not acceptable.
4 – 5.99	Do “Must-do” actions.
6 – 7.99	Do “Ideal” actions.
8 - 9	Do “Leadership” actions.

There is a threshold value for each dimension and this is set at 4 out of 9. Main dimensions below 4 are unacceptable and should be restructured. Other index scores for the main dimensions and their explanation are shown in Table 6.11. This scale is inspired the toolbox evaluation logic for assessing ethical principles for AI presented by Canca (2020). The obtained results are shown in Table 6.12.

According to the scores obtained as a result of the index calculation and the action plans in Table 6.2, the following results are obtained for the digital education system:

Table 6.12: Final results of DETI

Main Components	Scores	Actions
Ethical	7.044	Do “Ideal” actions.
Beneficial	5.980	Do “Must-do” actions.
Responsible	5.367	Do “Must-do” actions.
Explainable	5.245	Do “Must-do” actions.
Fair	7.446	Do “Ideal” actions.

- The digital education system evaluated seems to be at a good ethical level. With an index value of 7.044, it would be appropriate to take "Ideal" actions. In this context, the system should comply with the curriculum. Architectures for a trustworthy digital education should be created and awareness should be raised to promote a trustworthy mindset.
- The evaluated digital education system needs to implement "Must-Do" actions in the beneficial main dimension with an index value of 5.980. Since the value obtained is at the limit, "Ideal" actions can also be applied. First of all Training and awareness should be provided to encourage a trustworthy mindset. All processes should be standardized.
- Likewise, "Must-Do" actions should be applied according to the responsible main dimension. In addition to standardizing all processes, awareness should be raised for a trustworthy environment.
- The explainable dimension of the digital education system has the lowest index value with 5.245. "Must-Do" actions should be implemented in this dimension. Processes should be standardized and explanation methods should be included in the processes.
- The fair dimension of the digital education system has the highest index value with 7.446. "Ideal" actions should be implemented in this dimension as well. Then "Leadership" actions can also be implemented. In this context, processes should be tested and verified. In addition, stakeholder engagement and a social environment should be ensured.

7. CONCLUSION AND PERSPECTIVES

In this chapter, the results of the studies carried out within the scope of the thesis, the contribution of the thesis to literature, the limitations of the thesis, and future studies are given.

7.1. Conclusion of Thesis

In recent years, technological developments in the fields of information and communication affect almost every area of life and cause significant change and transformation in the field of education. With the development of technology, distance education opportunities have increased, and many opportunities have emerged to integrate individual and mass education methods into a single structure.

The education system, which is changing owing to the development of digital technology, has accelerated as a result of the COVID-19 pandemic limitations that have occurred all over the world. Teaching took place from offline to online. The main point here is that with the change in the environments in which the teaching is carried out, the teaching methods also change. While governments are continuously looking for ways to sustain uninterrupted education, the level and quality of digital access have primarily determined the quality of learning. During the pandemic, traditional learning environments have been replaced by digital learning environments. Universities have used instructional management software and open-source digital learning technologies to offer online programs.

With the pandemic moving the education system to digital platforms, the use of digital technologies in the field of education is increasing. Benefiting from the facilitating power of technology in the future of learning constitutes a turning point for educational

institutions. In a way, this transformation enables us to remember the online development opportunities that existed in our lives before and this time to use them more effectively.

Technological developments not only affect educational institutions at general and specific levels but also sets of new skills that this new life and business ecosystem requires. It is the new education system combined with independent lifelong learning that will engender these skills.

At this point, this thesis models and analyzes digital education systems to address the digital education system in a multidimensional way. In this context, the aims of this thesis are to increase the effectiveness of digital education and to provide a framework for a digital education system with better quality and efficient outcomes, to evaluate existing digital education platforms, to design a metaverse-based education system with the URs and TRs, and to ensure that the digital education system is ethical, beneficial, responsible, accountable and fair.

In line with these aims, a detailed literature review process had been conducted. Through a detailed literature review, scientific studies, sectoral reports, and books were systematically examined and gaps in the academic literature are defined. These gaps are addressed and filled in the chapters of the thesis. Following the results of the conducted literature review, in these chapters, evaluation frameworks that consist of a model proposition and analytical approaches were proposed. The models proposed in the evaluation frameworks of the thesis study and the analysis process of these models were parts of a decision-making process based on expert opinions and they included many criteria.

MCDM is an approach designed to solve decision problems involving multiple criteria. It is difficult to make a decision when there is not enough information in decision-making problems that involve many criteria that affect each other in the real world. The evaluation of digital education systems also has a mixed structure and includes various and contradictory criteria. However, when the information is uncertain, it is difficult to

decide and rank among digital technologies. The fermatean fuzzy approach overcomes uncertainty by allowing experts to evaluate in words rather than numbers.

In this context, firstly, existing digital education platforms were analyzed. User expectations regarding the platforms were collected and the relative importance weights of these expectations were calculated with the fermatean fuzzy DEMATEL method. As a result, the expectations with the highest importance were found to be "self-efficacy of the student (E42)", "system security (E15)", and "availability (E34)". Then, digital education platforms were evaluated using the fermatean fuzzy MACONT method and the most useful platform that appeals to users the most was determined as "Microsoft Teams".

Secondly, a novel metaverse-based education system was designed. In this chapter, the proposition of an integrated methodology was aimed at determining and evaluating the URs and TRs for assessing digital technologies for metaverse-based education. In this context, an integrated fermatean fuzzy AHP-based QFD methodology was developed and applied. The importance of URs was calculated with the fermatean fuzzy AHP technique. TRs and main digital technologies were evaluated with fermatean fuzzy QFD based on the FFDWPMM operator. According to the results, the most appropriate digital technology that meets URs has been determined as "Blockchain".

Lastly, a digital education model was created for the digital education system to be reliable by following a user-oriented approach. Based on the components of this model, the trustworthiness index of the digital education system was calculated. While calculating this index, the fermatean fuzzy PIPRECIA method was used to calculate the weights of the components and according to the results of the method, the components with the highest degree of importance were determined as "Data protection (C36)", "Human agency and oversight (C11)", and "Verifiability (C41)". As a result of the calculation of the trustworthiness index of the selected education system, it was determined in which dimension and which components it should pay attention to. Then, action plans that can be implemented according to the index values obtained are proposed.

The contributions of this thesis to the literature were as follows:

- This thesis contributes to the literature by providing a structured overview of publications on Education 4.0, supporting professionals, researchers and education system designers by identifying and discussing research gaps, and being the first study in the literature to provide a taxonomy and review of the concept of Education 4.0.
- It contributes to the literature by proposing an evaluation model that includes user expectations and evaluating existing digital education platforms with an integrated fermatean fuzzy DEMATEL - MACONT approach.
- The other contribution of this thesis is to design a metaverse-based digital education system consisting of URs and TRs with QFD approach and to evaluate digital technologies for a metaverse-based education system using fermatean fuzzy AHP method.
- Another contribution of this thesis is to provide an index-based evaluation model for a trustworthy digital education system and propose action plans based on the DETI approach with fermatean fuzzy PIPRECIA to fill the gaps in the literature.

7.2. Limitations and Future Works

This thesis is state-of-the-art research in the field of digital education. It models and designs digital education systems and addresses the digitalization of education. As with any research, this study is not without limitations. This thesis has also encountered several limitations. The following areas summarize these potential limitations:

- The theoretical limitations of the study are related to the scope of the research. The proposed evaluation models have been created in the most comprehensive way possible by taking studies in the literature, industrial reports, and expert opinions. However, the models could be extended.
- The methodological limitations of the study are related to the subjective focus of the analysis. The linguistic judgments expressed by the experts are based on their past knowledge and experience and subjective evaluations. Although the

most qualified experts in their field were selected for this thesis, the number of experts could be increased.

- Although the models were created by taking the opinions of different users, models could be created and compared for each different user.

The future research trends on digital education given below are based on this detailed study as well as the authors' past working experiences. Further analysis of these suggestions can generate new knowledge and sound theories in the field of digital education. The following areas are therefore suggested:

- The introduction of technology into our lives brings with it some problems such as privacy, intervention in private life, and an array of other ethical problems. In this context, creating the cyber security infrastructure of digital education more securely could be another direction.
- The quality of digital technology providers is directly proportional to the quality of the digital system. In this context, studies about assessing and determining the service provider that will provide the best digital technologies could be presented.
- Generic models could be differentiated and compared for different users and applied in different areas.
- In this thesis, the Education 4.0 approach is examined by considering higher education (universities). The effects of the Education 4.0 approach on education in the industrial business world could be examined and analyzed and this approach could be interpreted with industrial case studies.
- In parallel with the developments in digital technologies, studies could be carried out on the point at which the concept of Education 5.0 will enter our lives and what kind of expansions it will make in the field of education.

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APPENDIX

Table A.1: Papers concerning "Education 4.0" keyword

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2017	Ciolacu et al.	to evaluate the performance of student with machine learning methods	Research Paper	-	General Education System	-	Machine Learning	Neural networks, cluster analysis
2017	Ciolacu et al.	to present Education 4.0 concept with artificial intelligence algorithms	Research Paper	-	Higher Education	Engineering Education	Artificial Intelligence	-
2017	Eichinger et al.	to present Education 4.0 concept	Research Paper	-	Higher Education	Engineering Education	-	-
2018	Mogoş et al.	to analyze the main technologies of Education 4.0	Research Paper	-	Higher Education	Engineering Education	Robots, 3D Virtual Worlds, Cloud Computing	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2018	Maseleno et al.	to present revolutionazing Education 4.0 with e-learning and big data	Research Paper	-	General Education System	-	Big data	-
2018	Maria et al.	to give a view of the current trend in the industrial revolution and education system	Research Paper	Malaysia	Higher Education	-	-	-
2018	Hartono et al.	to produce a model of Smart Hybrid Learning Method	Research Paper	-	General Education System	-	-	Three layer architecture
2018	Ciolacu et al.	to predict the final score of students before participating in final examination	Research Paper	-	Higher Education	-	Artificial Intelligence, Machine Learning, Smart sensors	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2018	Sulaiman et al.	to present an educational tool to assist primary school children in self-directed learning	Research Paper	Malaysia	Primary Education	-	-	-
2018	Jeganathan et al.	to propose a discipline-independent framework for the curriculum of Education 4.0	Research Paper	-	Higher Education	Engineering Education	-	-
2018	Martin et al.	to summarize the emerging trends in education	Research Paper	-	General Education System	-	Augmented Reality	-
2018	Le Van Thang & Dung	to present the higher education 4.0 model in the armed forces to meet the changes of Industry 4.0	Research Paper	-	Higher Education	Education in Armed Forces	-	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2018	Benešová et al.	to present education requirements for electronics manufacturing within concept Industry 4.0	Research Paper	-	General Education System	Industrial Education	Augmented Reality	-
2018	Tanriogen	to determine the possible affects of Industry 4.0 on the Turkish Educational System	Research Paper	Turkey	Higher Education	-	Autonomous Robots, Internet of Things, Big Data, Augmented Reality	-
2018	Buasuwat	to discuss gaps and key challenges facing higher education in Thailand	Research Paper	Thailand	Higher Education	-	-	Statistical methods

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2018	Ramirez-Mendoza et al.	to describe a new curriculum for Engineering Education 4.0	Research Paper	-	Higher Education	Engineering Education	-	-
2018	Mourtzis et al.	to present the utilization of cyber-physical systems for Education 4.0	Research Paper	-	General Education System	-	Cyber-Physical Systems	-
2019	Mohd Adnan et al.	to examine the struggles of English educators at Malaysian public universities who are frantically trying to apply Education 4.0 learning technologies to teach this international language	Research Paper	Malaysia	Higher Education	Language Education	Virtual Reality	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2019	Terkowsky et al.	to present online education for manufacturing technology	Research Paper	Germany	Higher Education	Engineering Education	-	-
2019	Mogoş & Bodea	to present recommender systems for Education 4.0	Research Paper	-	Higher Education	Engineering Education	-	Association rule mining
2019	Juan et al.	to present an educational tool for social transformation	Research Paper	-	Secondary Education	Art Education	Virtual Reality	-
2019	Nikitakos et al.	to present a combination of instructional and communicative learning for Shipyard production	Research Paper	-	General Education System	Industrial Education for Shipyard Workers	-	-
2019	Waghid	to present the need of Education 4.0 for education institutions	Review Paper	Southern Africa	Higher Education	-	-	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2019	Miranda et al.	to describe how Open Innovation Laboratories are used as enabling resources to reach the vision of Education 4.0	Research Paper	Mexico	Higher Education	-	Internet of Things, Augmented Reality, Virtual Reality	-
2019	Silva & Nadais	to present a model for Education 4.0	Review Paper	-	General Education System	-	-	-
2019	Ab Rahman et al.	to provide an insight into gamification and its ability to instill students' engagement	Research Paper	-	Higher Education	-	-	-
2019	Shahbodin et al.	to support career of autistic learners with technology	Research Paper	-	General Education System	Education for autistic students	-	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2019	Kloos et al.	to present educational technologies	Research Paper	-	General Education System	-	Cloud Computing, Machine Learning	-
2019	Mourtzis et al.	to present the design and evaluation of a manufacturing system	Research Paper	-	General Education System	Industrial Education	-	Simulation
2019	Jedaman et al.	to present policies and strategic plan for Education 4.0	Review Paper	Thailand	General Education System	-	-	-
2019	Sethakul & Utakrit	to present challenges and future trends for education in Thailand	Research Paper	Thailand	Higher Education	Engineering Education	-	-
2020	Koul & Nayar	to propose a conceptual model of the holistic learning educational ecosystem	Review Paper	-	General Education System	-	-	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2020	Peredrienko et al.	to present the effect of education 4.0 for the new language learning	Review Paper	-	General Education System	Language Education	-	-
2020	Bujang et al.	to investigate the demand for digital learning platforms and tools	Research Paper	Malaysia	Higher Education	-	-	-
2020	Polyakova	to present Education 4.0 concept for engineering education	Editorial Note	-	Higher Education	Engineering Education	-	-
2020	Butt et al.	to present the structure of the concept of Education 4.0 with the integration of Industrial Revolution	Review Paper	Pakistan	General Education System	-	Internet of Things, Artificial Intelligence	-
2020	Jamaludin et al.	to explore the readiness and change involved in the implementation of Education 4.0	Research Paper	Asia	Higher Education	-	-	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2020	Buzov	to reveal the importance of Education 4.0.	Research Paper	-	Preschool Education	-	-	-
2020	Aristin et al.	to develop innovative learning media	Research Paper	Indonesia	General Education System	-	3D Map	-
2020	Ishak & Mansor	to explain to which extent the university is ready to face Education 4.0 challenges	Research Paper	Malaysia	Higher Education	-	-	Statistical methods
2020	Cárdenas & Inga	to propose a novel methodological strategy based on the usage of meaningful learning with emerging technologies	Research Paper	-	Higher Education	Language Education	Internet of Things	-
2021	Kinal	to present the historical outline of teacher education assumptions	Research Paper	Poland	General Education System	-	-	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2021	Kizilkaya et al.	to identify the opportunities the 5G networks can bring to Education 4.0	Review Paper	-	General Education System	-	Artificial Intelligence, 5G Technology	-
2021	Wasilah et al.	to produce variables that significantly influence the flexibility of IT management in the university	Research Paper	-	Higher Education	-	-	Statistical methods
2021	López et al.	to present a framework based on educational model	Research Paper	Mexico	Higher Education	-	-	-
2021	Miranda et al.	to present core components of Education 4.0	Research Paper	-	Higher Education	Engineering Education	-	-

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2021	Sarango-Lapo et al.	to present a evidence-based educational model	Research Paper	-	General Education System	-	-	Statistical methods
2021	Gutiérrez-Martínez et al.	to present the process of a teaching implementation methodology	Research Paper	-	Higher Education	Engineering Education	Internet of Things	
2022	Jain & Jain	to examine the acceptance and use of one of the IoT-based learning management systems	Research Paper	Oman	Higher Education	-	-	Statistical methods
2022	Ghavifekr & Wong	to investigate the students' academic performance	Research Paper	Malaysia	Secondary Education	-	-	-
2022	Verma et al.	to present a reliable irregularity-detection framework	Research Paper	-	General Education System	-	Internet of Things, Cloud Computing	Bayesian network

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2022	González-Pérez & Ramírez-Montoya	to present a framework	Review Paper	-	General Education System	-	-	-
2022	Gonzales et al.	to compute the priority roles of stakeholders to overcome the barriers	Research Paper	-	General Education System	-	-	Fermatean fuzzy entropy-based CRITIC-CODAS-SORT
2022	Oliveira & de SOUZA	to guide the design and application of teaching and learning experiences	Research Paper	-	General Education System	-	-	-
2022	Turan-Güntepe & Abdüsselam	to develop a reliable Education 4.0 competency determination scale	Research Paper	-	General Education System	-	-	Statistical methods

Table A.1: Papers concerning "Education 4.0" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application area	Education level	Specific education area	Used technology	Used methods
2023	Mubarak & Selimin	to assess the importance of learning skills	Research Paper	Abu Dhabi	Secondary Education	-	-	Statistical methods
2023	Dao et al.	to present a bibliometric analysis	Review Paper	-	General Education System	-	-	-
2023	Salinas-Navarro et al.	to develop digitally enabled experiential learning spaces	Research Paper	-	Higher Education	Engineering Education	-	-
2023	Haque et al.	to present a systematic meta-analysis	Review Paper	-	General Education System	-	Blockchain	-
2023	Almacen et al.	to develop an education preparedness indicator system	Research Paper	-	Higher Education	-	-	FUCOM
2023	Asad & Hussain	to examine the effect of Educations 4.0	Research Paper	Pakistan	Higher Education	-	Virtual Reality	Statistical methods

Table A.2: Papers concerning "Education 4.0 related" keyword

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2017	Enright et al.	to present the use of digital technology in physical education	Research Paper	-	General Education System	Physical Education	-	-
2017	Baert et al.	to present the use of digital technology in physical education	Research Paper	-	General Education System	Physical Education	-	-
2017	Barker et al.	to develop digital technology competence in physical education	Research Paper	-	General Education System	Teacher Education	-	-
2018	Bond et al.	to present the digital transformation of education	Research Paper	Germany	Higher Education	-	-	-
2018	Zabatiero et al.	to present the the pedagogical use of technology in education	Research Paper	Australia	General Education System	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2018	Madsen et al.	to present the effect of different national strategies of implementing digital technology	Research Paper	Norway, New Zealand	General Education System	Teacher Education	-	-
2018	van Rossum & Morley	to present the role of digital technology in the assessment of children's movement competence during physical education lessons	Research Paper	-	Primary Education	Physical Education	-	-
2018	Sargent & Casey	to explore pedagogies of digital technology in physical education	Research Paper	-	General Education System	Physical Education	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2018	Walinga et al.	to present the use of digital technology in physical education	Research Paper	-	General Education System	Physical Education	-	-
2018	Bowes & Swanwick	to present the use of digital technology in physical education	Research Paper	New Zealand	General Education System	Physical Education	-	-
2018	Kushzhanov et al.	to present the digital transformation of education system	Research Paper	-	General Education System	-	Virtual Reality	-
2018	Kaminskyi et al.	to present the digital transformation of university education	Research Paper	Ukraine	Higher Education	-	-	-
2018	Kapur et al.	to present the digital transformation of education	Review Paper	-	General Education System	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2018	Ntebutse & Collin	to present the digital equity in education	Research Paper	-	General Education System	-	-	-
2019	Sargent & Casey	to illustrate a way to teachers' use of digital technology	Research Paper	-	General Education System	Physical Education	-	-
2019	Xiao	to present a systematic review for digital transformation in education	Review Paper	China	Higher Education	-	-	-
2019	Jackson	to examine the pitfalls and pivots of digital transformation in education	Research Paper	-	General Education System	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2019	Liu et al.	to develop of the massive open online courses at higher education	Research Paper	China	Higher Education	-	-	-
2019	Androutsos & Brinia	to develop a pedagogy for teaching innovation in education	Research Paper	-	Secondary Education	-	-	-
2019	Curran et al.	to present the digital technology usage in continuing professional education	Research Paper	-	General Education System	-	-	-
2019	Torres-Ruiz & Moreno-Ibarra	to present the challenges and opportunities in the digital transformation of the higher education	Research Paper	Mexico	Higher Education	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2019	Chacon-Diaz & Brown	to present the integration of digital technology in education	Research Paper	USA	Higher Education	-	-	-
2019	Roberts-Yates & Silvera-Tawil	to explore the role of digital technology in the provision of educational opportunities for students who have been diagnosed with an intellectual disability	Research Paper	South Australia	Secondary Education	-	Virtual Reality	-
2019	Marjanović	to present a questionnaire for digital Technologies in education	Research Paper	Bosnia and Herzegovina	General Education System	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2019	Schereret al.	to present the technology acceptance model in education	Research Paper	-	General Education System	Teacher Education	-	Statistical methods
2020	Lazar et al.	to develop, validate and test an extended Technology Acceptance Model	Research Paper	Romaia	Higher Education	-	-	Statistical methods
2020	Mhlanga & Moloi	to present the digital transformation of education in COVID-19 process	Research Paper	South Africa	Higher Education	-	-	-
2020	Secundo et al.	to present the digital transformation of entrepreneurship education	Research Paper	Italy	Entrepreneurship Education	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2020	Viberg et al.	to present the integration of digital technology in education	Review Paper	Sweden	Secondary Education	Mathematics Education	-	-
2020	Rof et al.	to present the digital transformation for business model in education	Research Paper	-	Higher Education	-	-	-
2020	Abad-Segura et al.	to present a systematic review for sustainable management of digital transformation in education	Review Paper	-	Higher Education	-	-	-
2020	Madanipour & Cohrssen	to present the use of augmented reality for education	Research Paper	-	Preschool Education	Childhood Education	Augmented Reality	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2020	Calderón et al.	to explore the relationship between a student-centered digital technology approach and the pre-service teachers' intrinsic motivation	Research Paper	-	General Education System	Physical Education Teacher Education	-	Statistical methods
2020	Constantinou & Papadima-Sophocleous	to explain the use of digital technology in English Specific Purposes	Research Paper	Greece, the Republic of Cyprus	General Education System	Teacher Education	-	-
2021	Mohamed Hashim et al.	to develop a qualitative model that advocates how digital transformation as a propelling force	Research Paper	-	Higher Education	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2021	García-Peñalvo	to define a framework for introducing e-learning practices	Review Paper	-	Higher Education	-	-	-
2021	Valdés & Cerdá Suárez	to evaluate the involvement of an institutional ecosystem	Research Paper	Chile	Higher Education	-	-	-
2021	Cerdá Suárez et al.	to provide an overview of how relational elements configure management in higher education	Review Paper	Latin America	Higher Education	-	-	-
2022	Rof et al.	to understand the effects of the pandemic on the ongoing process of digital transformation	Research Paper	-	Higher Education	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2022	Bygstad et al.	to define a digital learning space	Research Paper	Oslo	Higher Education	-	-	-
2022	Okunlaya et al.	to define a qualitative content analysis to investigate extant literature	Review Paper	-	Higher Education	-	Artificial Intelligence	-
2022	D'Ambra et al.	to address digital transformation in higher education by exploring the engagement	Research Paper	Australia	Higher Education	-	-	Statistical methods
2022	Jiang et al.	to examine the different characteristics that virtual tools brought to online education	Review Paper	-	General Education System	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2022	Raza & Hasib	to provide a teaching methodology that combines project-based learning, self-regulated learning, and design projects	Research Paper	-	General Education System	-	-	-
2023	Deroncele-Acosta et al.	to identify positive cores of faculty	Research Paper	Latin America	Higher Education	-	-	-
2023	Antonopoulou et al.	to explore the underpinning mechanisms of an institution in managing digital transformation	Research Paper	UK	Higher Education	-	-	-

Table A.2: Papers concerning "Education 4.0 related" keyword (*continue*)

Year	Authors	Aim of the study	Article type	Application country	Education level	Specific education area	Used technology	Analytic methods
2023	Petchamé et al.	to present the salient perceptions of students and instructors in a master's program	Review Paper	-	Higher Education	-	-	-
2023	Quy et al.	to present a vision and approach of a university	Research Paper	Vietnam	Higher Education	-	Artificial Intelligence, Internet of Things	-
2023	Wang et al.	to evaluate the drivers for digital transformation	Research Paper	-	Higher Education	-	-	q-rung orthopair fuzzy sets- MEREC- SWARA- CoCoSo

BIOGRAPHICAL SKETCH

Esin MUKUL TAYLAN studied at Fahreddin Kerim Gökay Anatolian High School where she graduated in 2011. She obtained the B.S. and then master's degrees in the Industrial Engineering Department of Galatasaray University in 2016 and 2018, respectively. Since December 2017, she has been working as a research assistant in the Industrial Engineering Department of Galatasaray University. Currently, she is working towards Ph.D. degree in Industrial Engineering under the supervision of Prof. Dr. Gülçin BÜYÜKÖZKAN FEYZİOĞLU at the Institute of Science and Engineering, Galatasaray University.

Her research areas are multi-criteria decision making, advanced fuzzy logic and its applications, smart and digital systems, and digital technologies. She is the co-author of the research paper entitled “Digital transformation in education: A systematic review of education 4.0”, which is published in *Technological Forecasting and Social Change*, in 2023. She is also the co-author of several Science Citation Indexed papers and many proceeding papers in the field of Engineering.

PUBLICATION

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