EVALUATION OF THE SUPPLY CHAIN IN THE TURKISH CONSTRUCTION SECTOR WITH CIRCULAR ECONOMY PRINCIPLES

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ABSTRACT

EVALUATION OF THE SUPPLY CHAIN IN THE TURKISH CONSTRUCTION SECTOR WITH CIRCULAR ECONOMY PRINCIPLES

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The construction sector has countless adverse effects on the environment. With the recent concerns on sustainability, methods to make construction more sustainable have become a topic of interest. The circular economy was popularized as a concept to mitigate natural resource use, slow the use of materials, and close the cycle of waste materials. The construction sector holds the most immense potential in transitioning to a circular economy. Türkiye, as a developing country, urbanizes at a high velocity. Therefore, integrating sustainable practices through transitioning to a circular economy in the Turkish construction sector is urgent. However, no specific guideline for this transition exists in Türkiye. Therefore, this study aims to propose a framework for transitioning to circularity in Turkish construction supply chains and to present the existing state of circularity in the construction sector in Türkiye. Following this aim, a literature review was conducted on sustainability, supply chains, construction supply chains, and circular economy. Through the circular strategies and methods in the literature review, a framework was proposed for transitioning to a circular economy in Turkish construction supply chains. This framework was used to prepare a questionnaire that was distributed among Turkish construction firms. The questionnaire results were analyzed and evaluated, and statistical tests were conducted. The results found that while the type of staff and their level of education do not affect the circular methods used in the construction supply chain, awareness about circularity, use of circular strategies, and digital technologies directly affect the use of circular methods.

Keywords: Sustainability, Supply Chains, Construction Supply Chains, Circular Economy

ÖZ

TÜRK İNŞAAT SEKTÖRÜNDE TEDARİK ZİNCİRİNİN DÖNGÜSEL EKONOMİ PRENSİPLERİ İLE İNCELENMESİ

Yilmaz, Elif Naz
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İnşaat sektörünün çevre üzerinde sayısız negatif etkisi bulunmaktadır. Sürdürülebilirlik konusundaki endişeler attıkça inşaat sektörünü daha sürdürülebilir hale getirme yöntemleri konusundaki ilgi artmaktadır. Döngüsel ekonomi konsepti doğal kaynakların tüketimini azaltmak, malzeme kullanımını yavaşlatmak ve atık malzeme döngüsünü kapatmak amaçlarını güden bir kavram olarak ortaya çıkmıştır. İnşaat sektörü, döngüsel ekonomiye geçiş konusunda en büyük potansiyele sahiptir. Türkiye gelişmekte olan bir ülke olarak hızlı bir şekilde kentleşmektedir. Bu nedenle, döngüsel ekonomiye geçiş ile sürdürülebilir uygulamaların inşaat sektörüne entegre edilmesi aciliyet taşımaktadır. Ancak Türkiye'de bu geçişe ilişkin spesifik bir kılavuz bulunmamaktadır. Dolayısıyla bu çalışma, Türk inşaat tedarik zincirlerinde döngüselliğe geçiş için bir model önermeyi ve döngüselliğin mevcut durumunu araştırmayı amaçlamaktadır. Bu amaca ulaşmak için sürdürülebilirlik, tedarik zincirleri, inşaat tedarik zincirleri ve döngüsel ekonomi üzerine bir literatür taraması yapılmıştır. Literatür taramasında bulunan döngüsel stratejiler ve yöntemler ışığında, Türk inşaat tedarik zincirlerinde döngüsel ekonomiye geçiş için bir model önerilmiştir. Önerilen bu model, bir anketin hazırlanmasında kullanılmış ve bu anket "Şirket Bilgileri", "Döngüsellik Hakkında Farkındalık", "Şirket İşleyişinde Kullanılan Döngüsel Stratejiler" ve "İnşaat Adımlarında Kullanılan Döngüsel Yöntemler" olmak üzere dört bölümden oluşmaktadır. Bu anket, sektördeki döngüselliğin mevcut durumunu test etmek amacıyla Türk inşaat firmaları arasında dağıtılmıştır. Anket sonuçları her soru için ayrı ayrı analiz edilip değerlendirilmiş ve istatistiksel testler yapılmıştır. Sonuçlar, çalışan tipi ve çalışanların eğitim seviyesinin inşaat adımlarında kullanılan döngüsel yöntemlere etkisi olmadığını, fakat döngüsellik hakkında farkındalık, şirket işleyişinde kullanılan döngüsel stratejiler ve dijital teknolojilerin ise döngüsel yöntemleri direkt olarak etkilediğini göstermektedir.

Anahtar Kelimeler: Sürdürülebilirlik, Tedarik Zincirleri, İnşaat Tedarik Zincirleri, Döngüsel Ekonomi.

To my dear family…

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ABBREVIATIONS

AAC	Awareness About Circularity
AI	Artificial Intelligence
BIM	Building Information Modeling
CE	Circular Economy
CI	Corporate Information
CMUCS	Circular Methods Used in Construction Steps
CSCO	Circular Strategies in Company Operations
DfA	Design for Adaptability
DfD	Design for Deconstruction
GDP	Gross Domestic Product
GIS	Geographical Information System
IoT	Internet of Things
LCA	Life-Cycle Assessment
MRO	Maintenance, Repair, Overhaul
SDG	Sustainable Development Goals

CHAPTER 1

INTRODUCTION

This thesis consists of five chapters. This chapter initially presents the background and motivation of this study. It continues with the aim and objectives and then presents the procedure by outlining the stages of the study. This chapter ends with the disposition section, which presents an outline of this thesis.

1.1 Background and Motivation

The construction industry is known as a massive contributor to the depletion of natural resources and the damage given to the environment. Buildings and construction are responsible for 36% of energy use in the global realm and 39% of carbon dioxide (CO_2) emissions (El-Hakim and Abouzeid, 2024). As the world's population is increasing rapidly, the construction sector actively continues to provide people with dwellings. Kiss *et al.* (2015) state that by 2050, almost 70% of the population will dwell in cities as city migration continues. As concerns about sustainability have risen, integrating sustainability into the construction sector has become a topic of interest to reduce its environmental impact.

The supply chain is a relationship-based network that facilitates value creation (Pryke, 2009) and takes a massive role in the overall efficiency of a project. Traditionally, construction supply chains have been linear, based on a “take, make, dispose of” concept (Ghufran *et al.*, 2022). However, this linear form does not allow for a transition towards sustainability. The global use of primary materials like fossil fuels, metals, non-metallic minerals, and biomass is expected to double by 2060 (OECD, 2019). Furthermore, greenhouse gas emissions are expected to reach the 1.5

°C agreed in the Paris Agreement by 2030 (Teske, 2019). The circular economy (CE) has been popularized as a notion to minimize the use of natural resources, slow the use of materials, and close the waste cycle (Nikolaou *et al.*, 2021). With a circular economy, new material usage and waste generation can be minimized, unlike a linear economy. In this sense, integrating circular economy principles in supply chains has become many industries' goals. Associated with these concepts, transforming construction supply chains from a linear state to a circular state to achieve sustainability is vital in using resources more efficiently and minimizing environmental damage.

Globally, as little as 9% of the economy is circular since the traditional linear system is being used, with little effort being made to reduce, reuse, and recycle (Koç *et al.*, 2023). However, many guides and regulations regarding a transition to a circular economy exist, aiming to act as a catalyzer to the goal of mitigating climate change. For example, the Circular Economy Initiative in Germany presented a roadmap for transitioning to a circular economy, aiming for a prosperous circular economy leading to human well-being and value creation (Circular Economy Initiative Germany, 2021). Chile seeks to transition from a linear economy to a circular economy by 2040 by mitigating waste and pollution, circulating products and materials, and reviving nature (Ellen MacArthur Foundation, 2022). The Ministry of Infrastructure and Water Management of the Netherlands (2023) claims they aim to reach a completely circular economy by 2050 using raw materials for Dutch production and consumption. The Ministry of Environment, Urbanization, and Climate Change in Türkiye has also published a report assessing the country's potential to transition to a circular economy. Also, SKD Türkiye (2022) has published a report on Preliminary Research on the Circularity Potential of Five Sectors in Türkiye: the plastic packaging sector, textile sector, automotive sector, home appliances sector, and construction services sector.

There is a gap in the literature on achieving sustainability through the transition to a circular economy in the construction supply chains in Türkiye. The construction sector contributes heavily to the Turkish economy. In fact, according to the FIEC Statistical Report on Turkey (2021), the construction industry is held accountable for 5.4% of the total gross domestic product (GDP). It will employ 1.5 million people in 2020, while the sector's impact on the overall economy reaches 30%.

As a developing country, Türkiye continues to urbanize at a high velocity. Considering the vast impact that the sector has on the Turkish economy, transitioning Turkish construction supply chains to a circular economy would contribute heavily to the overall sustainability of the country. Even though Turkey is making considerable efforts to reach the European Union's carbon emission targets for 2030 and 2050, no guideline is specified for circularizing the Turkish construction supply chains to achieve sustainability, and a methodology for this transition is urgent. Therefore, this study aims to propose a framework for the transition towards a circular economy in construction supply chains in Turkey and investigate its potential. The primary motivator of this study is to answer the following questions:

- What actions can be taken to integrate circular economy principles into Turkish construction supply chains?
- Are Turkish construction companies aware of the benefits of circularity principles in construction supply chains?
- To what degree do Turkish construction companies apply circular economy strategies in their supply chains?

1.2 Aims and Objectives

This thesis proposes a framework for transitioning to a circular economy in Turkish construction supply chains. Furthermore, this thesis aims to present the current state of circularity in Turkish construction supply chains. Considering these aims, the following objectives have been identified:

- To investigate the actions to be taken for transitioning to a circular economy in Turkish construction supply chains through a literature review
- To develop a framework for transitioning to a circular economy in Turkish construction supply chains
- To test the proposed methodology through a questionnaire conducted with Turkish construction companies to see the current state of the circularity of Turkish construction supply chains.

1.3 Procedure

In this research, a thorough literature review is performed to investigate the actions that can be taken to transition to a circular economy in Turkish construction supply chains and how this transition contributes to sustainability. This literature review explores the concepts of sustainability, supply chains, construction supply chains, and circularity. These concepts must be thoroughly investigated to acquire the needed information for the framework proposal. Considering the information gathered through the literature review, a framework for the transition is proposed along with a questionnaire. This framework is then presented to Turkish construction companies to see the current state of circularity in Turkish construction companies. In the following step, the data gathered from the questionnaire was evaluated using statistical analysis methods. Finally, the results from the statistical tests are used to present the current state of circularity in the supply chains of Turkish construction companies.

1.4 Disposition

This thesis comprises five chapters. The first chapter is the introduction, in which the background information regarding this study and its motivation is presented, along with the aims and objectives of this study and its procedure.

The second chapter is the literature review on sustainability, supply chains and their management, construction supply chains and their management, and circularity.

The third chapter is the methodology, in which the materials and methods used in this study are explained. The material in this study is the proposed framework, which is derived from the information gathered through the literature review. The method of this study is explained in the second section of this chapter.

The fourth chapter presents the results of this study. Statistical tests are performed on the data collected from the questionnaire, and the proposed hypotheses are tested. The analyses and results of the hypothesis tests are presented and explained in depth.

The fifth chapter is the conclusion, which includes an outline of the study and its findings, presents a discussion, and finalizes with remarks for future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 The Concept of Sustainability

This section defines the concept of sustainability first, and a brief history is provided. The environmental, economic, and social pillars of sustainability are explained. Afterward, the Sustainable Development Goals (SDGs) of the United Nations are listed. Finally, sustainability is linked to the built environment.

2.1.1 The History of Sustainability

Sustainability was initially described by German forester and scientist Hans Carl von Carlowitz in the book "Sylvicultura Oeconomica" and later used by foresters for planting trees as a way of leading to "sustained-yield forestry" (Heinberg, 2010). Bartlett (2012) claims that in the 1960s and 1970s, many people realized that resource use and environmental degradation were rising dramatically and that this rise would push the limits of the finite productivity of the world and the availability of resources. Later, the term was popularized after 1987, when it was defined in the Brundtland Report from the United Nations' World Commission on Environment and Development as "sustainable development," being a development that satisfies the necessities of the current generation by taking into consideration the ability of the future generations to meet their needs. (Brundtland, 1987).

Many different definitions of sustainability exist in literature. Gomis *et al.* (2011) define sustainability as a term referring to acting morally and habitually, considering the effects given to the environmental, social, and economic realms, and acting consistently in harmony with those domains. Vos (2007) likens sustainability to security, as it aims to preserve a civilization while offering future generations various choices. Baumgartner and Quaas (2010) claim that sustainability is a normative idea regarding how humans should act towards nature and their responsibilities towards future generations and each other. Farley and Smith (2020) define the term "sustainable" as actions that consider the social, economic, and environmental effects of the decision-making process.

Heinberg (2010) formulated five axioms of sustainability to maintain a society over time, being:

1. Societies that continue not to use critical resources sustainably will fail.

2. The growth of population or growth in resource consumption rates cannot be sustained.

3. To achieve sustainability, renewable resources must be used at a rate lesser than or equal to the natural recovery rate.

4. To be sustainable, the nonrenewable resource use must continue at a declining rate, and this decline rate must be more extensive than or equal to the depletion rate, which is defined as the extracted amount that is used in a specified time interval as the percentage of the remaining amount to be extracted.

5. To reach sustainability, objects from human activities introduced to the environment should be diminished. If the pollution from the consumption and extraction of non-renewable resources continues and jeopardizes the ecosystems, the consumption and reduction of those resources must be reduced at a greater rate than the depletion rate.

Sustainable development comprises three interconnected pillars: environmental, social, and economic. Strange and Bailey (2008) state that these three pillars must be considered together in sustainable development, as people, habitats, and financial systems are related.

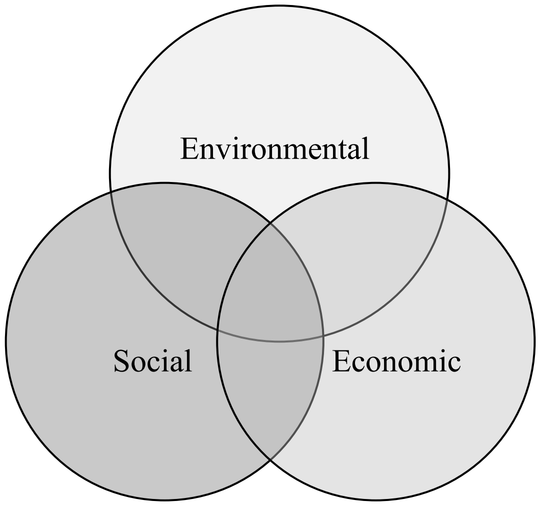


Figure 2.1. Pillars of Sustainability, derived from Gomis et al. (2011)

Gomis *et al.* (2011) state that environment does not refer to a simple external ecosystem but an experienced ecosystem that has conscious human life in its center and with which humans have a conscious and deliberate relationship. Environmental sustainability aims to minimize the negative impact caused by various factors on the environment, protect the available biodiversity, and preserve the natural environment (Ghimire, 2023). Furthermore, Khan *et al.* (2021) add that environmental sustainability as a conservation concept aims to balance the resources and services of present and future generations while avoiding any harmful acts to the wellbeing of the ecosystems that provide these resources and services. Even though sustainability is the most effortless to link with the environmental pillar, the economic and social pillars should also be considered to achieve sustainability.

Interlenghi *et al.* (2023) state that economic sustainability is a concept that aims to continuously grow the quantity of products and services that are provided in a specific time interval while increasing the total income of a determined group of people. Mohamed and Paleologos (2020) state that economic sustainability considers the distribution process of products, their consumption, production, and services rather than being a simple concept relating to gross national product, exchange rates, profit, and inflation.

Kandachar (2013) claims that social sustainability is the neglected pillar of sustainability. Balaman (2019) defines social sustainability as identifying and managing the positive and negative impacts of systems, procedures, organizations, and activities on human beings and social life. Popovic *et al.* (2013) claim that social sustainability aims to ensure people's socio-cultural and spiritual needs equitably, as the needs of people differ from one another and depend on society's present state. Social sustainability is one of the most vital aspects of sustainability, which seeks to improve the state of the world for people (Kraslawski and Turunen, 2013), on the contrary of being neglected.

2.1.2 Sustainable Development Goals (SDGs)

All United Nations member states agreed on the 2030 Agenda for Sustainable Development in 2015. The 2030 Agenda for Sustainable Development, a plan of action for people, planet, and prosperity (United Nations, 2015), involves 17 sustainable development goals (SDGs) (See Table 2.1.2). The Sustainable Development Goals Report published by the United Nations (2023) indicates that globally, we are falling behind in meeting the 2030 deadline, and we all must double our efforts to eliminate poverty and hunger, make progress in gender equality, and overcome climate change, nature and biodiversity loss and pollution.

Table 2.1. UN Sustainable Development Goals (https://sdgs.un.org/goals)

SDG Icon	SDG Name	SDG Icon	SDG Name
	No Poverty		Industry, Innovation, and Infrastructure
	Zero Hunger		Reduced Inequalities
	Good Health and Wellbeing		Sustainable Cities and Communities
	Quality Education		Responsible Consumption and Production
	Gender Equality		Climate Action
	Clean Water and Sanitation		Life Below Water
	Affordable and Clean Energy		Life on Land

Many industries have implemented sustainable strategies in their workflows to meet the sustainable development goals listed above. The built environment holds vast potential for implementing sustainable strategies due to its massive contribution to the depletion of natural resources.

2.1.3 Sustainability and the Built Environment

As concerns about sustainability continue to rise with the decrease in natural and energy resources and climate change, the sustainability of the built environment remains a hot topic among researchers. According to Fini *et al.* (2024), the built environment consists of man-made realms where people live and work, such as buildings, green areas, urban centers, and infrastructure. Younger *et al.* (2008) claim that as the global climate changes, many environmental effects occur, such as rising temperatures, elevating sea levels, heavy precipitation, extra heatwaves, and increasing drought. The intergenerational nature of sustainability is apposite in the built environment since structures affect the necessities and requirements of future generations (Sarkis *et al.*, 2009). According to El-Hakim and Abouzeid (2024), construction and buildings contribute 36% of global energy and 39% of carbon dioxide (CO_2) emissions. However, Berardi (2015) claims that the building sector holds the most significant potential for energy saving and pollution reduction, given its flexible nature.

Similarly, Pachouri *et al.* (2024) claim that the built environment is one of the areas that can help meet all the SDGs of the United Nations. GhaffarianHoseini *et al.* (2013) explain sustainability in built environments as an integrative approach to adapting environmental, economic, and social concerns in the design and building of architecture. Similarly, Sarkis *et al.* (2009) claim that decisions on the built environment must be made considering how the choices made on building systems and materials can affect the environment and society on broader dimensions. Pachouri *et al.* (2024) state that integrating sustainability into the built environment enhances and safeguards the natural environment, diversifying projects for the built environment to advance its interaction with nature. Fini *et al.* (2024) claim that transitioning towards circular, balanced, inclusive, and resilient built environments while achieving net-zero emissions is necessary.

2.2 The Concept of Supply Chain

This section initially explains the concept of supply chain with various definitions. Afterward, the structure of a supply chain is explained along with the types of activities performed.

2.2.1 What is a Supply Chain?

A supply chain is a relationship-based system that facilitates value creation (Pryke, 2009). Similarly, Sukati *et al.* (2012) state that a supply chain consists of activities that add value and tie suppliers and customers. A supply chain adds value to the input received from the suppliers and delivered to customers. All parties involved in the supply chain, such as manufacturers, suppliers, retailers, and customers, are bound to fulfill customers' requests (Chopra and Meindl, 2016).

Carter *et al.* (2015) perceive the supply chain as a network comprising nodes and links. Pryke (2009) states that as people seek other people with aspects they lack, firms seek to collaborate with other firms with aspects that complete them. Also, as people struggle to survive in isolation, isolated businesses would have similar difficulties. Similarly, Arshinder *et al.* (2008) claim that supply chains are circuitous entities embedding various activities that generally spread over many functions or organizations, and the members within a supply chain cannot compete independently.

2.2.2 The Structure of a Supply Chain

A supply chain comprises autonomous or semi-autonomous business entities through upstream and downstream links (Samaranayake, 2005). Arshinder *et al.* (2008) state that a supply chain includes different functions such as inventory, logistics, procurement and purchasing, production planning, organizational relationships, and performance measures. Waters (2003) claims that in a supply chain, activities in front of an organization that moves materials toward the interior are called upstream. In contrast, activities after the organization that move materials towards the exterior are called downstream (Figure 2). Within a supply chain, the upstream activities consist of tiers of suppliers, and downstream activities consist of tiers of customers (Waters, 2003). Similarly, Carter *et al.* (2015) state that a participant in a supply chain can be perceived as upstream towards its suppliers and downstream towards its customers.

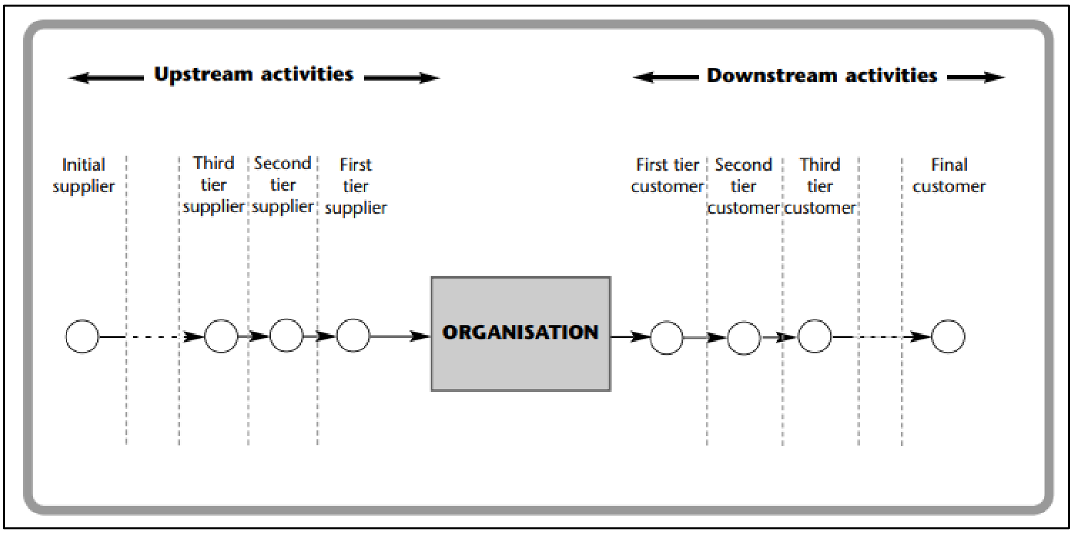


Figure 2.2. Activities in a Supply Chain (Waters, 2003)

2.3 The Concept of Supply Chain Management

This section explains supply chain management in depth with multiple definitions and its aims, history, processes, and differences from the logistics concept.

2.3.1 What is Supply Chain Management

Supply chain management (SCM) manages various relationships in a supply chain (Lambert and Cooper, 2000). Mentzer *et al.* (2001) perceived SCM as a phenomenon that guides the supply chain members to develop revolutionary solutions aiming to create distinctive sources of customer value.

SCM is about managing relationships within the supply chain instead of focusing on optimizing the separate parts of it (Lambert and Cooper, 2000; Larson and Halldorsson, 2004). It handles overall business processes and portrays an innovative method of managing businesses and relationships with other supply chain members (Lambert and Cooper, 2000). Similarly, Samaranayake (2005) argues that a supply chain comprises multiple components; thus, integrating information and the flow of materials among these partners from source to user is vital for effective management. All components involved in business processes within and across organizations must be integrated to achieve successful supply chain management (Samaranayake, 2005).

According to Samaranayake (2005), supply chain management seeks to provide speed-to-market, agility, and flexibility for quicker responses to customer demands while minimizing cost. To achieve the goals of supply chain management, the processes must be integrated at the operational level. Many complexities will occur if the components involved in a supply chain are incorporated within and outside organizations. Similarly, Lambert (2008) argues that profitability and competitiveness could improve if internal activities and business processes are managed through multiple companies.

2.3.2 History of Supply Chain Management

Li (2014) states that in the early 1960s, an MIT professor, Jay Forrester, studied the relationship between customers and suppliers, finding that the inventories in a supply chain pipeline portray fluctuating character as they move further from the customers. According to Shukla *et al.* (2011), producers followed mass production techniques in the 1950s and 1960s, intending to decrease production costs to produce minimal products in flexible processes. The 1980s portrayed an intensified global competition. Hence, organizations had to present reliable products with high quality, low cost, and more flexible design. As stated by Lambert and Cooper (2000), the term "Supply Chain Management" was initially mentioned by consultants at the beginning of the 1980s, and it has been the subject of attention ever since. Li (2014) states that in the early 1980s, Harvard Professor Michael Porter suggested that companies further manage the relationship of their inbound and outbound logistics, operations, sales and marketing, and customer services to be more competitive. According to Min *et al.* (2019), SCM practices became increasingly popular as information technology improved in the late 1990s.

2.4 Construction and Supply Chain Management

Implementing SCM in the construction sector is critical to achieving efficiency (Papadopoulos *et al.*, 2016; Prkye, 2009; Behera *et al.*, 2015). Behera *et al.* (2015) state that construction supply chain management (CSCM) extends beyond being a management trend; it allows considerable improvement in client and stakeholder value and cost reductions. According to RezaHoseini *et al.* (2021), CSCM aims to deliver projects on time with minimum cost. Similarly, Liao *et al.* (2023) state that CSCM helps firms optimize projects and enterprise performance by balancing numerous resources, collaborating with all primary participant enterprises, and integrating information.

Specific differences can be listed between construction supply chains and manufacturing supply chains. Vrijhoef and Koskela (2000) defined three characteristics of construction supply chains:

- A construction supply chain holds an intersecting character where all materials are directed to the project site, and the product is assembled there with the directed materials. Unlike manufacturing systems, where factories distribute multiple products to many customers, construction factories are concerned about a single product.
- Although there are exceptions, the construction supply chain is temporary since it produces one-time construction projects through a repetitive orientation of project organizations. Therefore, the construction supply chain is explained as instable and fragmented, alongside the differentiation of the design and construction of the built product.
- The construction supply chain is order-based, creating new products in each project. Although there are exceptions, repetition is rare. However, the process can be very akin to specific projects.

In a similar vein, Papadopoulos *et al.* (2016) listed some of these differences as:

- Often, each construction product is for a single client.
- Each project leads to a different product.
- For each project, the place, equipment, and production methods change.
- Construction personnel rotate often during the construction time and between projects.
- Every material and part cannot be stored at the site.

Behera *et al.* (2015) state that the typical construction project supply chain includes architects and engineers, main contractors, specialty subcontractors, and material suppliers. Pryke (2009) states that a construction supply chain typically consists of consecutive operations conducted by people who do not consider the other stakeholders. Construction projects are usually obtained through a process in which a project creates a focal point for a building process executed by a contractor, who is typically given the work by forming the lowest bid to complete the project. Balasubramanian and Shukla (2017) state that the main contractor either carries out the construction themselves or hires subcontractors for specific activities. The main contractor and subcontractor must rely on suppliers for raw materials and equipment.

Khalfan *et al.* (2010) claim that construction supply chains can be considered as activities related to transforming raw materials into finished products. A typical linear construction supply chain starts with a demand for construction from a client that needs a new building. Then, architects and engineers design the building, and a main contractor is selected to procure it. Raw materials are converted into building products considering the drawings the architects and engineers provided. The main contractor works with subcontractors to transform building materials into substructures, superstructures, services, and internal finishings. Then, the building is commissioned. Finally, the client takes over the building, and the building is occupied (see Figure 2.4).

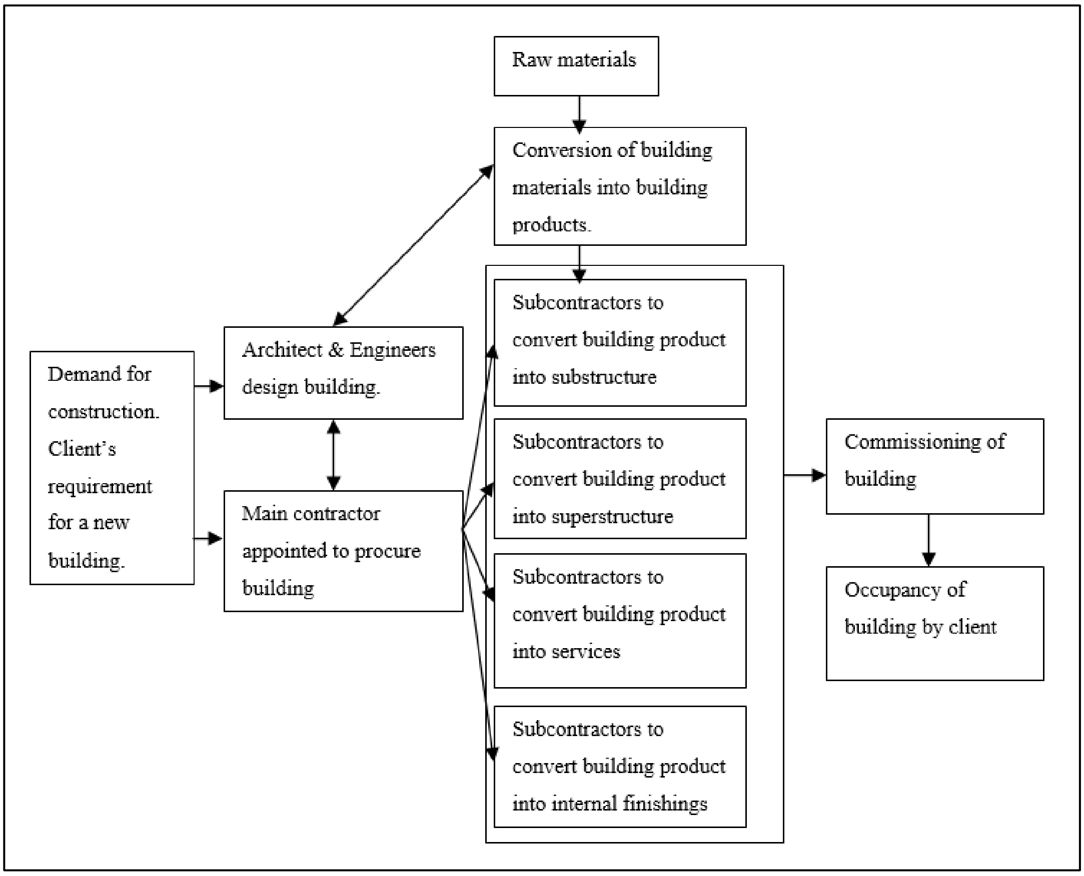


Figure 2.3. A Typical Construction Supply Chain, derived from Briscoe et al., 2001

2.5 The Concept of Circular Economy

In this section, the concept of circular economy is initially defined and explained thoroughly. Then, a circular economy's environmental, economic, and social benefits are explained.

2.5.1 What is Circular Economy

According to Nikolaou *et al.* (2021), the effectiveness and flow of the economy and production are highly affected by the depletion of natural resources. According to ARUP (2016), the conventional linear economy comprises a "take, make, use, dispose of" concept that stems from using energy from finite resources. Nikolaou *et al.* (2021) state that circular economy emerged as a concept to mitigate natural resource consumption, slow the use of materials, and close the cycle of waste materials (see Figure 6).

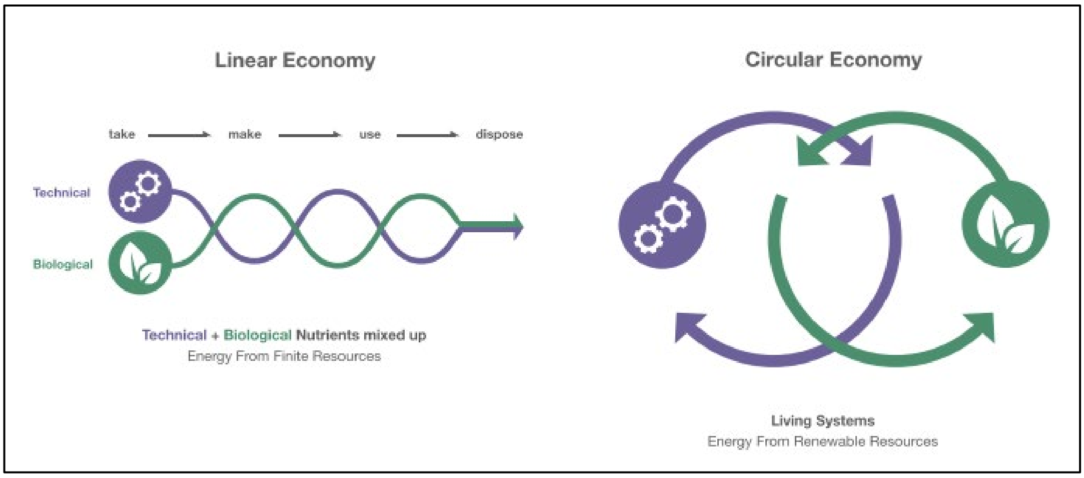


Figure 2.4. Linear Economy vs. Circular Economy (from ARUP, 2016)

The Ellen McArthur Foundation (2021a) states that the circular economy is a significant notion that can improve the well-being of citizens and the environment and contribute to tackling many global issues like climate crisis, waste and pollution, and resource depletion. Similarly, Kirchherr *et al.* (2017) claim that the circular economy is an economic domain that reinterprets the “end-of-life” by reducing, reusing, and recycling materials in production, distribution, and consumption. Geissdoerfer *et al.* (2017) state that a circular economy is a reviving structure that slows, closes, and narrows the material and energy loops to reduce resource consumption, emissions, and excess energy. They continue by stating that a circular economy can be obtained through designs made to last and maintain, in addition to Kirchherr's (2017) definition. Nikolaou and Tsagarakis (2021) claim that a circular economy presents a conversion from the conventional linear economy to a circular economy. The circular economy suggests returning the products at the end-of-life stage to the production stage, which were traditionally intended to be disposed of in landfills (Nikolaou and Tsagarakis, 2021). Furthermore, Zhang *et al.* (2021) claim that the circular economy presents a much more sustainable methodology than the linear economy, which adopts the “extract, make, use, dispose” mentality. Yu *et al.* (2022) add that the circular economy aims to minimize the adverse environmental impacts of the conventional linear economy and shift to a production system that restores and regenerates through the circular flow of materials while reducing and eliminating waste.

Potting *et al.* (2017) claim that there are several strategies to achieve circularity aiming to reduce the use of natural resources while minimizing waste production (See Table 2.5.1).

Table 2.2. 10 R Strategy, derived from Potting et al. (2017)

Smarter product use and manufacture	R0	Refuse	Make the use of a product unnecessary by leaving out its function or providing the same function in a different product.
	R1	Rethink	Use the products more thoroughly.
	R2	Reduce	Use less natural resources and materials and produce and use a product more efficiently.
Extend the lifespan of the product and its parts	R3	Reuse	Use a product that is in a good state and can offer its original function to another customer again.
	R4	Repair	Repair and maintain faulty products to be used with their original function.
	R5	Refurbish	Restore and update an aged product.
	R6	Remanufacture	Use the parts of a product disposed of in a new product offering the same function.
	R7	Repurpose	Use the parts of a product disposed of in a new product offering a different function.
Useful application of materials	R8	Recycle	Process materials to achieve the same (high grade) or lower (low grade) quality.
	R9	Recover	Energy recovery.

2.5.2 Benefits of Circular Economy

Schroeder *et al.* (2019) state that the circular economy could present unneglectable benefits such as creating jobs, cost savings, productivity, efficiency of resources, and innovation. According to Kumar *et al.* (2019), CE offers various social and political opportunities as it strengthens the relationship between industry and society. A circular economy closes the loop; therefore, all participants within the supply chain must extend their collaboration.

- **Environmental Benefits**

Junnila *et al.* (2018) state that a circular economy presents environmental benefits such as decreasing the need for primary production through secondary production, using fewer resources, increasing efficiency, and reducing greenhouse gas emissions by using renewable materials in primary production. Schroeder *et al.* (2019) claim that circular economy methods could reduce 7.5 billion tons of CO2 equivalent globally. The Ellen MacArthur Foundation (2021b) states that a circular economy decreases greenhouse gas emissions by implementing strategies that reduce emissions through value chains, keep hold of embodied energy in products, and isolate carbon in the soil. Walker *et al.* (2018) state that life-cycle assessment (LCA) methods generally evaluate the environmental benefits of recovering and recycling materials.

- **Economic Benefits**

According to Sehnem *et al.* (2019), value creation results from cost reduction, which can be obtained from reduced marginal costs, reduced costs regarding the purchase of virgin materials, reduced waste disposal, or lower environmental taxes. Value creation can also be created through enhanced profits by exchange flows, putting waste on the market as input material for another industry, producing energy from waste, and improving brand and reputation (Sehnem *et al.*, 2019). Furthermore, according to Van Ewijk (2018), implementing a resource-efficient circular economy has long-term and short-term benefits. In the long term, the economy can benefit from protecting vital natural resources for sustainability. In the short term, the benefits of a circular economy arise from savings on input material costs (Van Ewijk, 2018). Velenturf and Purnell (2021) state that a circular economy can limit costs and price volatility, reduce import dependency, and enhance resource security.

- **Social Benefits**

According to Nikolaou *et al.* (2021), a circular economy advances social and human rights by conserving natural resources for future generations and job creation for the current generation. Furthermore, Padilla-Rivera *et al.* (2020) list many social benefits of the circular economy, such as social equity, sharing economy, health and safety of workers and users, and participation and local democracy. Sehnem *et al.* (2019) add more social benefits to a circular economy, such as increased customer benefits, engaged employees, and eco-development.

2.6 Circular Economy and Construction

According to Wuni (2023), climate change, increasing competition in business, high costs of virgin materials, the changing industry culture and mindset, pressures in using sustainable business models, and innovative digital technologies draw attention to circular economy in the context of sustainability. The global rate of circularity decreased from 9.1% in 2018 to 8.6% in 2020 (Circle Economy, 2022). Wuni and Shen (2022) claim that the construction sector, with the most significant ecological footprint, is one of the biggest contributors to the expanding gap in circularity. ARUP (2016) claims that the engineering and construction sector consumes the most raw materials, constituting 50% of steel production globally and consuming more than 3 billion tonnes of raw materials.

Ghufran *et al.* (2022) claim that the traditional construction industry approach was based on a linear economy with a "take, make, dispose of" concept, which did not allow the constructed products to be taken to pieces and reused. This concept of the traditional linear economy mainly affects the circularity gap. Nasir *et al.* (2017) claim that sustainable supply chain concepts have been developed parallel to circular economy discussions. Similarly, Chen *et al.* (2022) state that the last decade has portrayed a view of using the circular economy as a realm to bear the idea of a new model development aiming to improve resource flows through Reduce, Reuse, and Recycle strategies. The field of construction has aspired to develop its value chain by slowing resource use by elongating the lifetime of the building, closing the resource loop by rerouting the End-of-Life (EoL) building elements, and narrowing the use of resources by efficient design and developing construction (Chen *et al.*, 2022).

The construction industry is among the sectors that hold tremendous potential in implementing circular economy strategies due to its distinct processes and offering environmentally friendly products and technologies. By incorporating circular economy principles in the European built environment, it is expected that €350 billion can be saved through resource and energy savings (Norouzi *et al.*, 2021). Koç *et al.* (2023) state that even though it is a complicated process to integrate a circular economy into the construction industry, as it may result in extra costs and efforts, a well-managed transition can result in severe economic and industrial opportunities that heavily contribute to achieving environmental goals, higher rates of employment and economic growth. Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment (2015) state that a built environment founded on a circular economy would provide people with buildings that generate power and food rather than consuming them, having fully closed water, material, nutrition, and energy loops.

In addition to promoting value maintenance and increasing circularity in biological and technical material cycles, circular construction eliminates waste and promotes a closed-loop structure in which the resource value and building components are maximized (Wuni, 2023). Chen *et al.* (2022) state that a circular economy in construction aspires to stop the use of virgin materials and waste generation and preserve resource value initially by reducing resource needs.

2.7 Integrating Circular Economy to Construction Supply Chains

Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment (2015) state that there are three principles of circular economy: conserving and improving the natural capital by maintaining limited stocks and managing the flows of renewable resources, optimizing resource productions by circulating products, components, and materials at a maximum rate of use in biological and technical cycles, and encourage efficiency in systems by revealing and designing out negative outwardnesses. These three principles of circular economy can be explained through 6 business actions, forming the ReSOLVE framework: REgenerate, Share, Optimize, Loop, Virtualize, and Exchange.

Table 2.3. ReSOLVE Framework, derived from Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment (2015)

Regenerate	Transition to renewable energy and materials; reclaim, retain, and regenerate the well-being of ecosystems; and replenish the biosphere with recovered biological resources.
Share	Minimize the product loop speed, optimize their use by sharing them with other users, reuse them over time, and extend their lifetime through maintenance, repair, and design for durability.
Optimize	Improve the product's performance and efficiency, eliminate supply chain and manufacturing waste, and use big data, automation, remote sensing, and steering.
Loop	Remanufacture goods or their parts, recycle materials, digest without requiring free oxygen, and obtain biochemicals from organic waste.
Virtualize	Virtualize through books, music, travel, online shopping, autonomous vehicles, etc.
Exchange	Replace old materials with cutting-edge, non-renewable materials, apply new technologies, and choose new products and/or services.

In their research, Vegter *et al.* (2020) listed eight processes in a circular supply chain. In the table below, the processes in italics are the added processes listed for a supply chain in a circular business model.

Table 2.4. Processes in a Circular Supply Chain (Vegter et al., 2020)

Process Level 1	**Process Level 2**	**Remarks**
Plan	Plan Supply Chain	Plan Supply Chain aims to establish how resource availability and the supply chain affect each other and the environment.
	Plan Source	
	Plan Make	
	Plan Deliver	
	Plan Use	*Plan Use seeks to schedule the necessities and resources of a supply chain in advance for maintenance and repair to increase product availability in the Use level.*
	Plan Return	
	Plan Recover	*Plan Recover seeks to schedule the requirements and resources of a supply chain to recover the returned products efficiently.*
Source	Source Stocked Product	A circular supply chain should focus on sourcing materials that can lead to return, disassembly, recovery, and minimizing waste.
	Source Make-to-Order Product	
	Source Engineer-to-Order Product	
Make	Make-To-Stock	*A circular supply chain should focus on resource-efficient production with an additional focus on product packaging for storage or delivery to end-users and collecting and getting rid of waste during production.*
	Make-To-Order	
	Make-To-Deliver	
	Packaging and Waste Disposal	
Deliver	Deliver Stocked Product	
	Deliver Make-to-Order Product	

Table 2.4. (continued)

	Deliver Engineer-to-Order Product	
	Deliver Retail Product	
	Deliver MRO (Maintenance, Repair, Overhaul) Product	*Delivering spare parts is necessary for maintenance and repair at the use level.*
Use	*Use*	*The use of the product by the end-user.*
	Maintenance	*Keep the product in the necessary state to fulfill its function.*
	Repair	*Restore the product adequately to fulfill its function.*
Return	Source Return Defective Product	
	Source Return MRO Product	
	Source Return Excess Product	
	Source Return End-of-Use Product	*After a product reaches its end-of-life, its end users become its product sources. Thus, take-back and buy-back initiatives must be formed.*
	Deliver Return Defective Product	
	Deliver Return MRO Product	
	Deliver Return Excess Product	
	Deliver Return End-of-Use Product	*Products must be collected and delivered to a facility at the end-of-life phase to allow for waste process and recovery.*
Recover	*Reuse*	*Reintegrate the end product into the supply chain with little to no change.*

Table 2.4. (continued)

	Remanufacturing	*Recover the components from the finished products and fuse them with new elements to create a new product that performs like the original.*
	Refurbishing	*Turn the end product into good condition by replacing or repairing its significant components and making changes to enhance its appearance.*
	Upcycling	*Turn materials into a new state with higher quality and functionality.*
	Recycling	*Recover materials for the original purpose or repurposing.*
	Downcycling	*Transform materials into a new state with lower quality and usefulness.*
Enable		Communicate with organizations and private persons.

Vegter *et al.* (2020) explain each supply chain process listed in the table above. The "Plan" process identifies the necessities of the supply chain and matches them with the accessible assets and resources. Supply chains in a circular business model must seek environmental boundaries, and the accessibility of natural resources must be a key consideration in the "Plan" process. The additional subprocesses in the "Plan" processes are given as "Plan Use" and "Plan Recover," as "Use" and "Recover" processes are added to the Level 1 Processes. The "Source" process schedules product deliveries, receives, verifies, and transfers the product, and authorizes supplier payment. In a circular business model, authorities must consider substitute materials to source in this process. The "Make" process schedules activities related to production, issues materials, produces and tests, stages, and releases products to deliver. The "Packaging and Waste Disposal" subprocesses are essential in a circular business model in the "Make" Process. Delivering goods to end customers is not the sole goal of the "Deliver" process, but this process also seeks to organize spare part delivery for maintenance to extend the product's lifetime; hence, the subprocess "Deliver MRO (Maintenance, Repair, Overhaul) Product" emerges. Consumption is part of circular business model supply chains, so "Use" is added as a Level 1 process. In the "Use" process, the product is used by the end-user and is maintained and repaired to extend the product's lifetime. End users are required to return their products as inputs at their end-of-life in a circular business model for the "Make" process; hence, the process "Return." As products can also be returned due to end-of-use, besides defects, MRO, and excess, the "Return End-of-Use" subprocesses are added to the "Return" process. A circular business model deeply concerns recovery activities; hence, the process of "Recover" is added as a Level 1 process, including subprocesses of Reuse, Remanufacturing, Refurbishing, Upcycling, Recycling, and Downcycling. Finally, the process Enable handles the management processes in the supply chain of a circular business model.

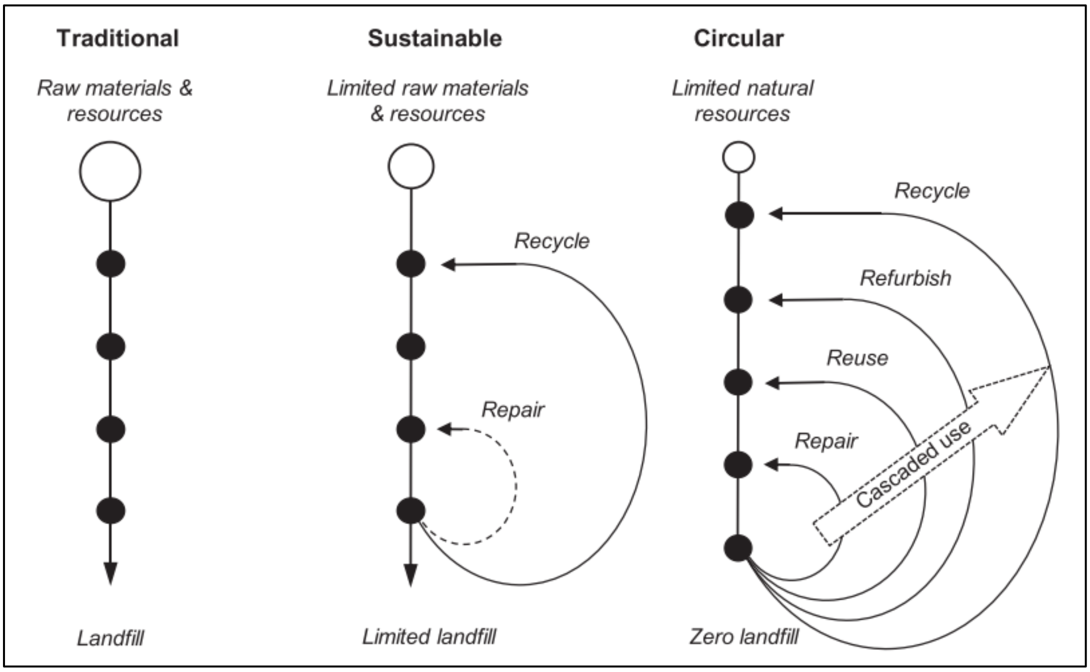


Figure 2.5. Types of Supply Chains (derived from De Angelis et al., 2018)

De Angelis *et al.* (2018) conceptualized traditional, sustainable, and circular supply chains in the figure above. It can be seen from the figure that in the traditional supply chains, raw materials and resources end up directly in landfills. In sustainable supply chains, limited raw materials and resources end up in limited landfills, with repair and recycling techniques used along the way. In circular supply chains, the input material is limited natural resources that lead to zero landfill, with repair, reuse, refurbish, and recycle techniques being used through the chain.

The construction industry is becoming more and more aware of circular economy principles. According to Norouzi *et al.* (2021), construction is one of the three sectors with massive potential for incorporating circular economy strategies. However, the goals of a circular economy still have a long way to go in the construction industry since construction and demolition waste constitutes 46% of global waste generation (Ding *et al.*, 2023). Többen *et al.* (2022) state that a circular building process would differ from traditional building processes as other supply chain partners are involved, structures of material and product ownerships change, and new income flows are created. Chen *et al.* (2022) state that a circular economy in construction preserves the resource value and prevents virgin material use and waste outputs primarily through reducing resource necessity, along with recycling and reusing materials. A circular economy in the building sector optimizes current and future resource loops by narrowing, slowing, and closing resource loops (Eberhardt *et al.*, 2021).

2.8 Phase-Specific Strategies to Integrate Circular Economy Principles into Construction Supply Chains

In this section, some phase-specific principles for integrating circular economy principles into construction supply chains are investigated and explained in depth. The phases are split into four categories to refine and present the activities clearly: the design phase, manufacturing and construction phase, operation and maintenance phase, and end-of-life phase.

Table 2.5. List of Phase-Specific Circular Methods

Design Phase	Design with LCA
	Design with reused materials
	Design with recycled materials
	Design for deconstruction
	Design for adaptability
	Design with customer feedback
Manufacturing and Construction Phase	Production of safe, resource-efficient materials
	Use of renewable and biobased materials
	Creation of material passports
	Prefabrication of elements
	Use of green construction methods
	3D printing of elements
Operation and Maintenance Phase	Service life planning
	Tracking of building performance and emissions
End-of-Life Phase	Diversion of wastes
	Identification of reusable and recyclable components
	On-site waste management
	Upcycling
	Downcycling
	Reverse logistics

2.8.1 Design Phase

- **Design with Life-Cycle Assessment (LCA)**

Nasir *et al.* (2017) claim that Life-Cycle Assessment (LCA) estimates the environmental impacts of all life cycle stages. Larsen *et al.* (2022) state that from a value chain perspective, the initial stage of LCA is extracting raw materials, followed by their production and use, up to waste treatment. Chen *et al.* (2022) state that integrating LCA in the design phase supports CE principles by narrowing the resource loops and reducing material use and cost in construction. Eberhardt *et al.* (2021) state that when LCA is applied in the early design stage, it holds vast potential to minimize the adverse environmental impacts of a building's life cycle.

- **Design with Reused Materials**

According to Huovila and Westerholm (2022), the reuse of materials is one of the critical points of the circular economy in construction, as it decreases the need to extract virgin materials. Spisakova *et al.* (2022) claim that design is a crucial phase to increase the use of reduce, reuse, and recycle principles. Chen *et al.* (2022) state that design with reused materials is vital in avoiding waste generation. Furthermore, if reuse is integrated into the design stage, it helps improve reusability in the end-of-life phase. Minunno *et al.* (2018) claim that building reuse is rarely preferred in the construction industry since authorities prefer demolition instead of deconstruction since deconstruction is time-consuming. The building components should be stored, tested, and certified. Furthermore, due to the necessary analyses to integrate the concept of reuse in the design phase, the design process takes longer, and more costs are needed (Kozminska, 2019).

- **Design with Recycled Materials**

Akponovo (2023) claims that recycling, transforming waste into valuable materials, presents an alternative strategy to remove waste with benefits such as resource protection and minimizing greenhouse gas emissions. Chen *et al.* (2022) state that designing with recycled materials is a method that can be used to maintain the flow of materials to reduce waste generation. According to Hendriks (2002), recycling primary raw materials, such as sand, gravel, clay, and oil, is possible due to their homogenous nature. However, recycling secondary raw materials comes with many processes, such as recognition, sorting, reduction of size, and separating.

- **Design for Deconstruction (DfD)**

Akinade *et al.* (2020) define deconstruction as a scenario for the end-of-life of buildings, allowing for recovering building components focusing on material reuse. Chen *et al.* (2022) claim that design for deconstruction helps close material usage flows and minimize the environmental impact of buildings at the end-of-life phase, drawing attention to the importance of material compositions and choices for successful design for deconstruction. According to Munaro and Tavares (2023), deconstruction effectively reduces construction and demolition waste creation, reduces greenhouse gas emissions, decreases landfill loads, preserves natural resources, and increases the construction sector's environmental awareness.

- **Design for Adaptability (DfA)**

Askar *et al.* (2022) define adaptability as a concept that ensures that the spatial, structural, and functional aspects allow for flexibility in a building against changing operational variables throughout time. Munaro and Tavares (2023) claim that while an adaptable building can be transformed to meet users' constant needs and demands, most buildings are designed regardless of their future adaptability, aiming to be designed and constructed following their current use. Minunno *et al.* (2018) state that design for adaptability allows for the planning of flexible places and the designing of adaptable components to minimize waste generation due to adjustments in the operational stage of buildings. Hamida *et al.* (2022) state that adaptability creates a backbone for integrating circularity in buildings, as it paves the way to reach a closed and reversible chain.

- **Design with Customer Feedback**

Karna and Junnonen (2005) claim that being aware of the satisfaction level of your customers is essential as a goal, measurement tool, or success factor while developing construction projects and supply chains. A case study by Jokinen *et al.* (2023) found that authorities gathered user experiences from the end customers and analyzed the data to improve the experience presented to them by circular solutions. The feedback was utilized to enhance the value of the circular solutions. Furthermore, Calzorali *et al.* (2022) claim that companies collaborate to achieve feedback loops to achieve self-sustaining production methods and use materials multiple times in circular supply chains.

2.8.2 Manufacturing and Construction Phase

- **Production of Safe Resource Efficient Materials**

Huovila and Westerholm (2022) state that producing resource-efficient materials with low carbon footprints and high recycled content is critical in achieving circularity in the manufacturing stage. Amarasinghe *et al.* (2024) state that prefabricated elements decrease labor intensity and increase resource efficiency. Huovila and Westerholm (2022) add that this stage necessitates making sustainable and circular materials available to ensure the aimed outcomes and extra value are achieved in the other stages.

- **Use of Renewable and Biobased Materials**

Le *et al.* (2023) define "circular bio-based building materials" as materials that comprise biological origins that can be reprocessed and used as raw building materials in construction. According to Keena *et al.* (2022), using bio-based materials leads to adaptable systems. Dams *et al.* (2023) give some examples of bio-based materials that can be incorporated into construction, such as cotton stalks, cork, hemp, flax, and agricultural straws.

- **Creation of Material Passports**

Çetin *et al.* (2023) define material passports as instruments providing digitalized qualitative and quantitative data on a product's attributes to support circular principles of narrowing, slowing, closing, and regenerating. Similarly, Tokazhanov *et al.* (2022) claim that material passports give insight into material characteristics and history of use that help create value in the later recycling process. Çetin *et al.* (2023) also claim that material passports can be made at various scales, such as material, product, or building, to aid multiple circular strategies, such as design optimization to enhance recyclability.

- **Prefabrication of Elements**

Amarasinghe *et al.* (2024) define the prefabrication of elements as manufacturing the components of a building structure at an off-site facility and assembling these components on-site. Huuhka *et al.* (2023) claim that the prefabrication of elements increases the reusability of components. According to Zairul (2021), prefabricated elements contribute to circularity by enabling shorter project plans, improved site protection, enhanced product quality, cost savings, and waste reduction.

- **Green Construction**

Balasubramanian and Shukla (2017) claim that green construction can be defined as practices conducted on-site to mitigate the environmental impacts of the construction process. Many benefits arise with green construction, including maximized resource efficiency, enhanced life quality and customer satisfaction, flexibility, the potential to cater to changes in the future, and natural and social environments. Wibowo *et al.* (2019) state that green construction aims to optimize resource conservation and obtain savings in four resource areas: energy, land, water, and materials.

- **3D Printing of Elements**

According to Khan *et al.* (2023), the 3D printing of elements in construction contributes heavily to transitioning to a circular economy by using input materials from construction and demolition waste. Fonseca and Matos (2023) claim that by using 3D printing in construction, the creation of waste can be decreased by 30-60%, and time can be deducted by 50-70%. Furthermore, since 3D printing is conducted through Artificial Intelligence and Building Information Modeling tools, it helps create jobs and mitigates limitations such as workforce in construction (Fonseca and Matos, 2023).

2.8.3 Operation and Maintenance Phase

- **Service Life Planning**

Bourke and Kyle (2019) claim that service-life planning aims to make sure that the service life of a building will at least be equal to its design life, much better if it exceeds it. According to Chen *et al.* (2022), service life planning relates to the reuse of materials in various life cycles, and codes such as ISO 15686 Standards on Buildings generally define service life for reused materials (Bourke and Kyle, 2019).

- **Tracking of Building Performance and Emissions**

Aranda-Mena and Vaz-Serra (2021) state that the operation and maintenance phase accounts for a considerable amount of emissions, and the adequate management of a building throughout its occupancy holds massive importance, considering the operational energy and carbon emissions. Huovila and Westerholm (2022) state that in the operation and maintenance phase, users and facility managers should track the performance and emissions of the building, maintaining the building to keep the value of the building on track.

2.8.4 End-of-Life Phase

- **Diversion of Wastes**

Chen *et al.* (2022) state that stakeholders can choose between diverting materials from landfills and transporting them to landfills. To achieve circularity in construction supply chains, the diversion of wastes holds vast importance in the building's end-of-life. Ratnasabapathy *et al.* (2020) define diversion of wastes as the process in which the waste is redirected from landfill facilities through numerous strategies, such as the reuse and recycling of components.

- **Identification of Reusable and Recyclable Components**

Akanbi *et al.* (2019) claim that although the reusability of building components and materials directly affects the performance of buildings in the end-of-life phase, proper consideration has not been given to the reusability of building materials as a performance measure at the end-of-life phase of buildings. Furthermore, according to Akanbi *et al.* (2018), identifying recoverable components and measuring their potential performance is essential for enhancing the secondary material market in a circular economy.

- **On-Site Waste Management**

Yuan *et al.* (2013) claim that generally, a positive idea forms around on-site waste management, in which construction waste is diverted on construction sites according to its characteristic aspects. Bao and Lu (2020) claim that on-site waste recycling has multiple benefits, such as cost reductions in investment, transportation, and pollution minimization. However, stationary recycling plants must support on-site waste management, which has limited capacity, constraints around the site, project duration, and equipment availability (Bao and Lu, 2020).

- **Upcycling**

Vegter *et al.* (2020) define upcycling as turning materials into a new state with higher quality and functionality. According to Wang *et al.* (2021), unneglectable benefits come with upcycling, such as improved construction waste management efficiency by eliminating the need for new material purchases. With the help of extra resources and third-party involvement, companies may obtain high savings (Wang *et al.*, 2021).

- **Downcycling**

Vegter *et al.* (2020) define downcycling as turning materials into a new state with less quality and functionality. Similarly, according to Vilcekova *et al.* (2023), downcycled materials are less strong than the original materials, and new material addition is required to acquire similar strength. Minunno *et al.* (2018) claim that while steel and concrete are recyclable materials, in most cases, concrete is downcycled.

- **Reverse Logistics**

Badi and Murtagh (2019) state that end-of-life management maximizes the reuse of a product's materials through reverse logistics and circular economy. Saygılı and Karabacak (2022) state that reverse logistics is the coordinated transfer of used materials from the destination to the start point for assessment, reuse, or destruction through recycling methods. According to Jing (2019), reverse logistics is vital in green supply chain management practices and helps achieve higher financial performance. The materials and products that can be reused are returned from the end users to the producer to be recrafted and reused.

2.9 Digital Technologies for Circularity

Digital technologies in construction supply chains are vital for transitioning to a circular economy. Khan *et al.* (2022) claim that using digital technologies may result in decreased consumption of resources and material needs and more straightforward implementation of circular practices. According to Banihashemi *et al.* (2024), digitalizing construction includes the automation of all phases of construction, bringing many benefits such as increased efficiency, reduced challenges, sustainability in a general context, and the innovative use of building materials. Some digital technologies to be used in transitioning to a circular economy in construction supply chains are obtained from the literature and are explained below.

- **Building Information Modeling (BIM)**

BIM is the digital representation of the constructed asset. Xue *et al.* (2021) state that BIM usage in construction has a high potential to bring sustainability since it helps select materials, minimizes waste, creates alternatives for energy savings, estimates costs, and contributes to green building design. BIM contributes to circularity by slowing and closing the resource loop by containing vital data on building geometry, material assets, and the number of building components. Chen *et al.* (2022) state that BIM-integrated LCA results in optimizations in design and construction.

- **Internet of Things (IoT)**

Atta (2023) defines IoT as a digital system comprising physical assets connected through identifying and sensing communication and processing sensors. IoT includes electronic devices that simultaneously work with a network connection, which can communicate with each other and control the acts of assets. These devices are integrated into physical assets and transfer data through the Internet. IoT is vital for supply chains due to its ability to collect and transfer data, providing unneglectable benefits to circularity.

- **Artificial Intelligence**

Artificial Intelligence (AI) comprises simulations conducted by machines and computers, which provide problem-solving mechanisms by imitating human intelligence. According to Oluleye *et al.* (2023), it can support the transition to a circular economy in the construction industry in design and optimization due to its ability to solve complex and non-linear problems, making rapid predictions and generalizations.

- **Big Data**

Big Data tackles massive amounts of data that grow repeatedly and are hard to contain and analyze. Banihashemi (2024) claims that integrating Big Data in construction can easily define risk and improve the decision-making process, leading to sustainability in the construction sector.

- **Blockchain**

Chen *et al.* (2022) claim that Blockchain handles decentralized computation and data storage and is characterized by trust and security. Incorvaja *et al.* (2022) claim that many benefits come with using Blockchain, which identifies as evidence of certification and identity, such as enhanced product security, trust, transparency, and reliance between various realms within supply chains.

- **Geographic Information System**

GIS is a computer system that analyzes and visualizes coordinates. Tsui *et al.* (2024) claim that GIS is used to create, share, and analyze spatial data in the built environment that stems from data sources like satellite images. With its systemic, visual, and quantitative nature, GIS can be used for waste management and to create a life cycle assessment (LCA) base.

- **Digital Twins**

Digital twins create a virtual representation of the environment, working with real-time data through sensors that analyze a physical asset. According to Koutamanis (2024), digital twins can be integrated with BIM, acting as a predecessor to digital twins, acting with the same symbolic approach. Also, digital twins can be integrated with other strategies, such as material passports, to help reuse building components at the end-of-life phase.

2.10 Bibliometric Analysis

To further analyze the existing publications regarding circular construction supply chains, a bibliometric analysis was conducted. The data used in this bibliometric analysis was retrieved from Scopus (www.scopus.com) and analyzed using VOSViewer version 1.6.20. The search for publications was conducted by entering the keywords "circular AND construction AND supply AND chain" among "Article title, Abstract, Keywords." To select publications that are up to date, the search was refined by filtering the year range between 2008 and 2024, and 296 documents were found. The data from the documents was exported in CSV format to be analyzed in VOSViewer.

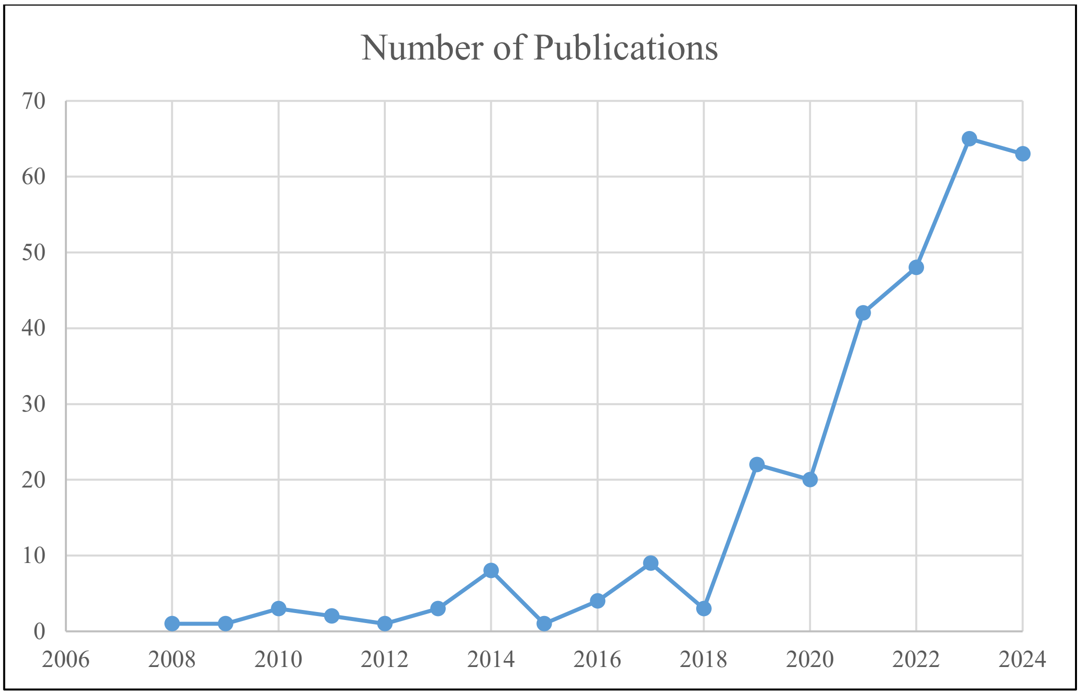


Figure 2.6. Number of Publications per Year

The number of publications by year is presented in Table 2.10.1. The period between 2019-2024 saw an upward trend among publications on circular construction supply chains. This increase proves the eagerness in the sector to transition to a circular economy, as organizations show great interest in this transition. The publications will likely increase in the year 2025 as the trend of circular construction supply chains continues.

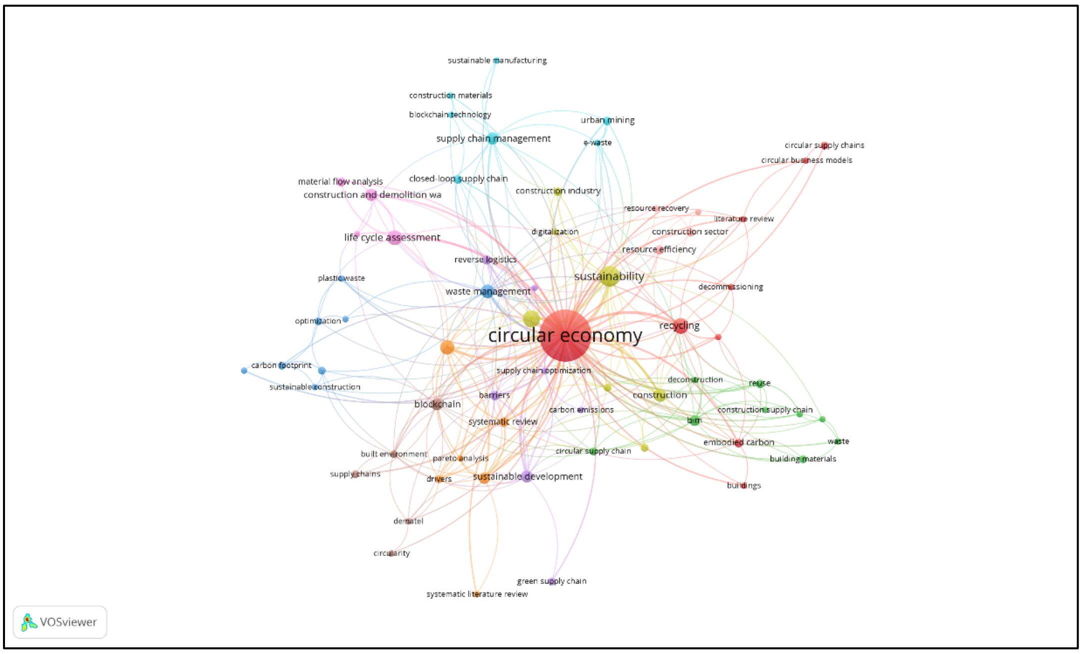


Figure 2.7. Co-Occurrence of Keywords

The co-occurrence mapping technique was used in VOSViewer to analyze the relationships between the keywords in the obtained publications. In the software, a minimum of three occurrences of a keyword was applied as a limiting factor to see the relevant keywords. 66 out of 856 keywords (8%) fulfill the criterion. Ten clusters were created by VosViewer, showing the relationship between the keywords. The red cluster is the most extensive among the ten clusters, consisting of the topics of circular economy and buildings. It can be seen from the co-occurrence analysis that the total link strengths of supply chains and circular supply chains are pretty low, constituting 6 and 3, respectively. It can be seen from the co-occurrence mapping that supply chains and circular supply chains show links with the concept of circular economy. However, these links are not as prominent.

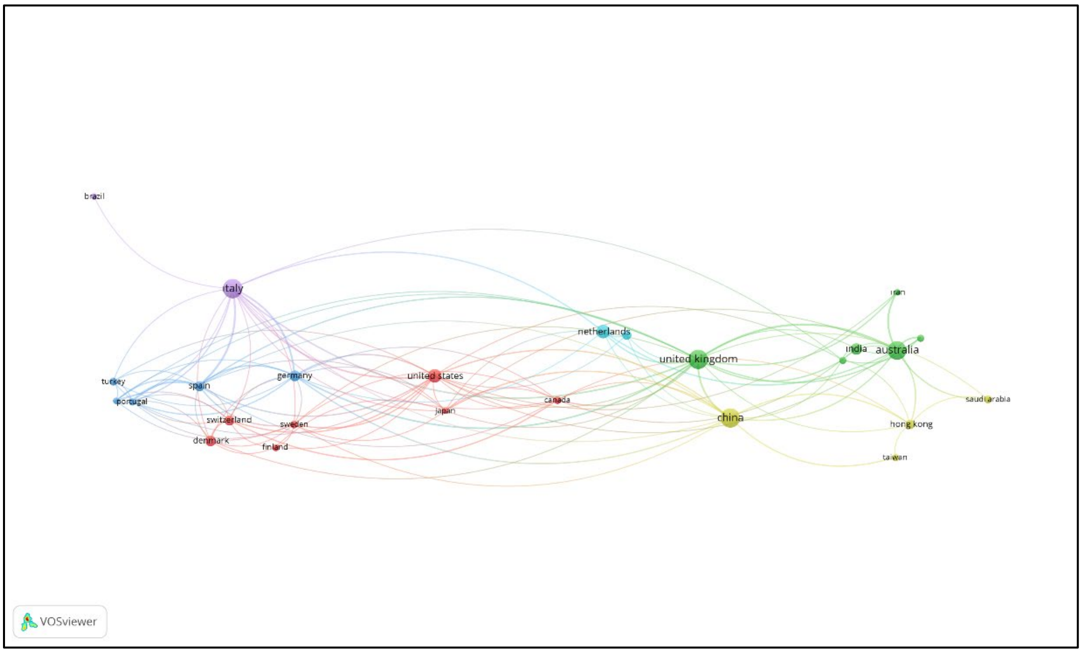


Figure 2.8. Countries Analysis

Figure 2.10.2 represents the co-authorship where countries are used as a unit of analysis. The analysis was conducted by limiting the minimum number of documents per country to five. Among the 63 countries, 26 meet the threshold. Table 2.10.2 shows the top 5 countries contributing 61% of the publications.

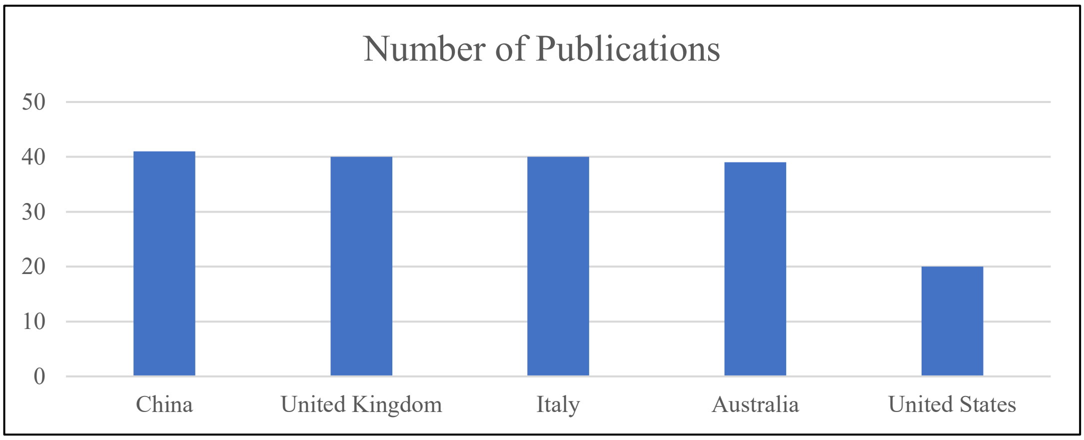


Figure 2.9. Top 5 Countries that Contributed to the Publications

2.11 Inferences Drawn from the Literature Review

Sustainability is a realm that considers the effects on the environmental, social, and economic realms while considering future generations. The members of the United Nations agreed on the 2030 Agenda for Sustainable Development, which involved 17 sustainable development goals. Nations attempt to comply with these sustainable development goals to eliminate adverse environmental, economic, and social effects. As concerns about sustainability continue to rise with the decrease in natural and energy resources and climate change, the sustainability of the built environment remains a hot topic among researchers. Integration of sustainability in the construction industry is vital in today's world, where multiple adverse environmental effects occur.

Supply chains are systems that create value through activities and relationships, tying suppliers and customers. A supply chain consists of upstream links that move materials inwards and downstream links that move materials outwards. Supply chain management tackles business processes and managing relationships with other supply chain members. Many processes are embedded in supply chains, with each one being in a relationship with the other. Supply chain management is usually mistaken for logistics. However, it differs from logistics since it concerns relationships between several organizations.

Construction supply chain management differs from manufacturing supply chain management since it has specific characteristics such as the products being directed to the site and assembled on-site concerning a single product, consisting of temporary projects characterized as one-time assets, and creating new products in each project due to their order-based nature. Traditionally, construction supply chains adopt a linear approach. Initially, a demand is commissioned for the building. Then, designers and architects create the project, and a main contractor procures the building. In this process, raw materials are turned into built assets, and finally, the building is occupied.

The circular economy is popularized to mitigate natural resource consumption, slow the use of materials, and close the cycle of waste materials, contributing to sustainability in the construction industry. The circular economy in the construction sector draws attention to the end-of-life phase, promoting the reduction, reusing, and recycling of materials in the construction supply chain. It presents the idea of returning the products at the end-of-life stage to the whole phases of the construction supply chain. It aims to overwrite the traditional "extract, make, use, dispose of" approach. As the construction industry is among those with substantial adverse effects on the environment, transitioning to a circular economy in the construction sector has become a topic of interest. Construction supply chains can be improved by integrating circular strategies such as slowing resource utilization by elongating the lifetime of buildings, closing the resource loop by turning the end materials to the previous stages of the construction supply chain, and narrowing the use of resources by effective design and construction. Three strategies are obtained from the literature review: the 10 R Strategy, the ReSOLVE Framework, and Circular Supply Chain Processes. These strategies help create a guideline for transitioning to a circular economy in supply chains and construction supply chains. Furthermore, many phase-specific strategies and digital technologies can be listed for this transition.

The bibliometric analysis shows that circular construction supply chains have become a topic of interest, especially between 2019 and 2024. The keyword most used among the analyzed publications is circular economy, and the links of circular economy with supply chains are not as prominent as the links with other keywords. Furthermore, Türkiye is not among the countries with the most publications. Hence, this research is highly important in Turkish circular construction supply chain literature.

CHAPTER 3

MATERIAL AND METHOD

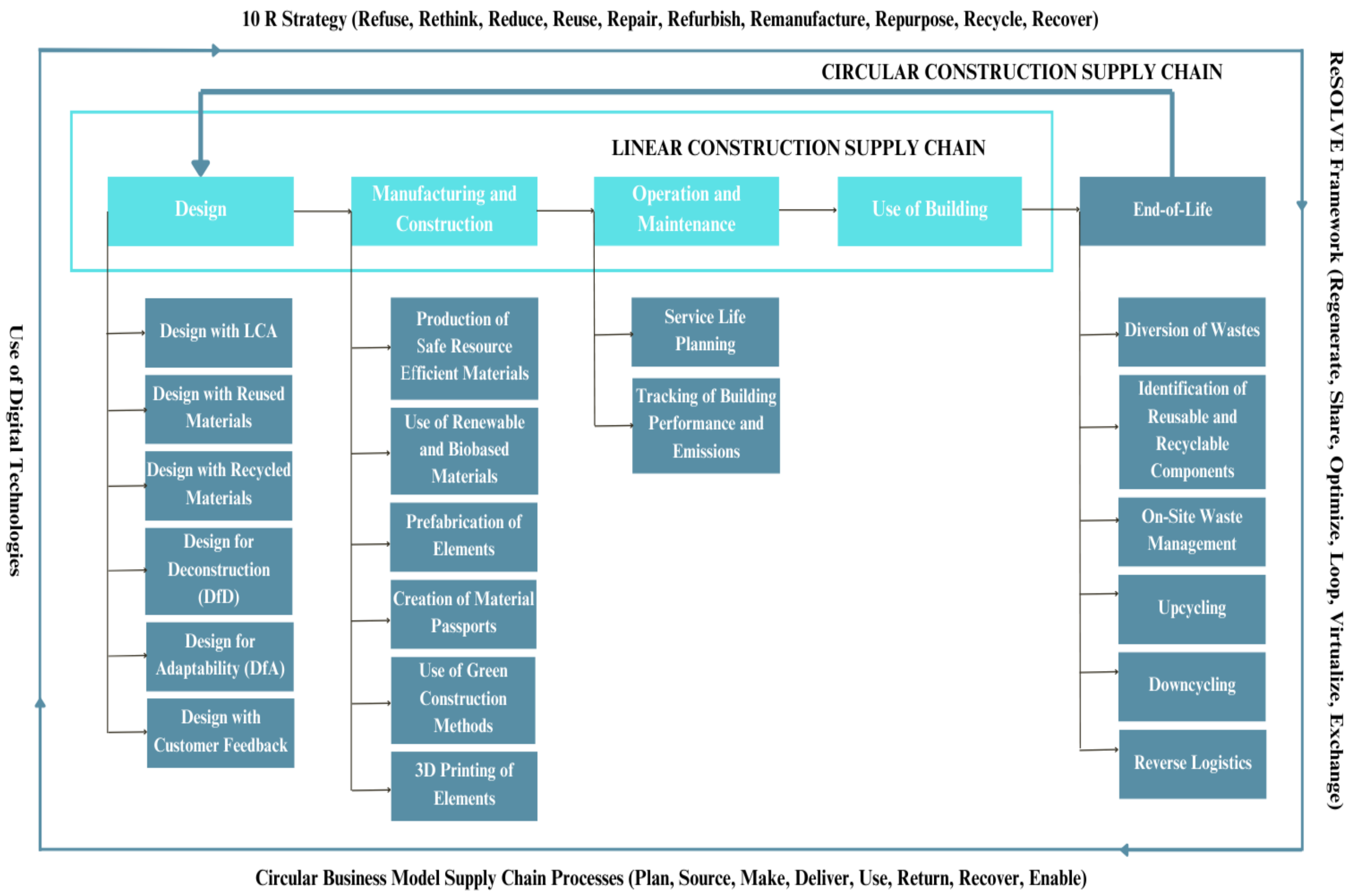
3.1 Introduction

This chapter explains the research material and methodology used to collect and analyze the data in detail. Initially, the research population and the method of sampling are presented. Then, the framework developed for the research is explained in depth. Afterward, the data compilation, conducted through a questionnaire, is described in depth. Finally, the data analysis is explained in depth. Through the questionnaire that was prepared in light of the proposed methodology, this research investigates the existing state of the supply chains of Turkish construction companies in terms of circularity. This research aims to present a picture of the Turkish construction sector in terms of circular steps taken in the supply chains and to raise awareness of the concept of circularity in the Turkish construction industry.

3.2 Material

In light of the thorough literature review, some strategies and methods for transitioning to a circular economy in the construction industry were identified. With the aim of this research being to present a picture of the existing state of circularity in Turkish construction supply chains, a framework was developed including all these strategies and methods categorized and distributed according to the sequential steps of the construction supply chain (See Figure 3.2).

Figure 3.1. Framework for a Transition to Circularity in the Turkish Construction Sector



In developing the framework, a simplified construction supply chain is presented with four phases: design, construction, operation and maintenance, and use of the building. This simplified construction supply chain is in the traditional linear form, comprising a "take, make, use, dispose of" concept that stems from using energy from finite resources. The framework adds the End-of-Life stage to the linear construction supply chain. However, a circular loop is created by linking the End-of-Life practices to the design phase. Furthermore, circular methods that can be used in the steps of the construction supply chain derived from the literature review are proposed. Also, circular strategies that can be used in the company operations are given. These strategies were also derived from the literature review, namely the 10 R Strategy (see Chapter 2.5.1), the ReSOLVE Framework (see Chapter 2.7), and Circular Business Model Supply Chain Processes (see Chapter 2.7). Lastly, digital technologies are proposed to transition to a circular economy. All methods and strategies are obtained from the literature review and are explained in the previous chapters.

A questionnaire was prepared to present the existing state of circularity in Turkish construction supply chains. The questionnaire consists of four parts, each aiming to examine a different aspect of circularity within Turkish construction supply chains. The first part includes questions on the number of staff types and their level of education. The second part contains questions about the respondents' awareness of circularity. The third part investigates the circular strategies used in company operations, and the fourth part investigates circular methods used in construction steps and digital technologies. The questionnaire was prepared according to the proposed framework, with questions investigating the circular strategies and methods listed in the framework.

To achieve the primary goal of investigating the existing state of circularity in Turkish construction supply chains, the population of this research was initially defined as construction firms that are members of the Turkish Contractors Association (TCA) and Turkish Construction Industrialists' Employers Union (INTES). All construction firms registered to these associations were considered the population of this research. The questionnaire was sent to these construction firms via e-mail, consisting of approximately 200 e-mails. However, this method of gathering data failed due to two reasons. The first reason was the lack of participation from the construction firms since the firms associated with the organizations mentioned above were relatively low in quantity. The second reason was the large scale of the companies based on the number of employees. To investigate the existing state of circularity in Turkish construction supply chains from a broader perspective, mid-scaled and small-scaled companies were aimed to be investigated along with the large-scaled firms. Therefore, three experts in the construction field were consulted to select mid-scaled and small-scale construction firms. The experts were chosen unbiasedly based on availability among those with over twenty years of industry experience, relying on their considerable opinions.

3.3 Method

The questionnaire was sent to approximately 250 construction firms via e-mail, including large-scaled, mid-scaled, and small-scaled companies. Among these 250 construction firms, 62 responses were collected (24.8%). Of the 62 responses, 17 firms did not complete the survey; therefore, these uncompleted responses were discarded from the research. The questionnaire was completed with 45 completed responses, constituting an 18% completion rate. Among the respondent companies, 15 have 0-10 employees, 16 have 10-50 employees, 10 have 50-250 employees, and four have more than 250 employees. The data-gathering process through the administered questionnaire began on 13.05.2024 and ended on 16.07.2024.

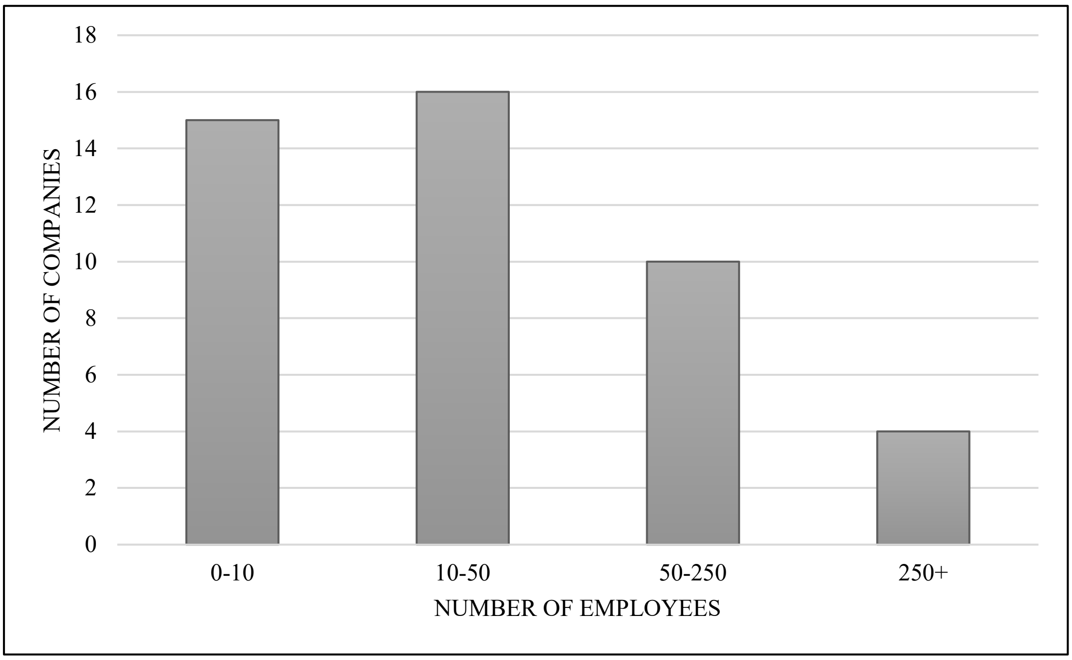


Figure 3.2. Number of Employees of the Respondent Companies

The questionnaire consists of 4 parts: corporate information, awareness about circularity, circular strategies used in company operations, and circular methods used in the construction steps.

The first part, "Corporate Information," aims to gather information about the company and the respondent, consisting of 3 questions. The first question includes four sub-questions, asking for basic information about the company and the respondent. The second question consists of four sub-questions asking for the number of the types of staff, which are "Administrative," "Technical," "Non-Technical," and "Other." The third question includes four sub-questions asking for the level of education of the staff, being "Undergraduate," "Graduate," "PhD," and "Other."

In the second, third, and fourth parts, all questions are asked on a 1-5 Likert scale (1=very low, 5=very high) to organize, analyze, and present the responses. The second part, "Awareness About Circularity, " aims to see the respondents' awareness of the circular economy and its relationship with sustainability and the construction sector. This part consists of 5 questions. These questions aim to measure the respondent's thoughts on the existing state of construction and its effects on the environment, along with the awareness of circularity and its benefits.

The third part, "Circular Strategies in Company Operations," aims to gather information about the circular strategies used in the operations of the respondents' companies. This part consists of 3 questions. Three strategies are presented in three respective questions: Circular Business Model Supply Chain Processes (adapted from Vegter *et al.*, 2020), the ReSOLVE Framework (Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment, 2015), and the 10R Strategy (Potting *et al.*, 2017), all of which are proposed within the framework as strategies to be integrated into the construction supply chain. The questions aim to measure the level of usage of these three strategies by companies in their operations. These strategies are explained in depth in the literature review.

The fourth part, "Circular Methods Used in Construction Steps," aims to gather information about the circular methods used in the steps of the construction supply chain of the respondents' companies. This part consists of 5 questions. The first four questions ask the respondent company to mark their level of usage of the methods to achieve a circular supply chain in the four phases of the construction supply chain, being the design phase, the manufacturing and construction phase, the operation and maintenance phase, and the end-of-life phase, respectively. The last question asked the respondent's company to mark their level of usage of 7 digital technologies. The methods and digital technologies given within the questions are all within the proposed framework and are explained in depth in the literature review.

3.4 Statistical Data Analysis

For the data analysis, initially, the questionnaire results that were given on a 1-5 Likert scale were tabularized and analyzed using Microsoft Excel. The respective qualitative data supported these results. Afterward, four hypotheses were tested using statistical analysis methods.

The statistical analyses in this research were conducted using SPSS (Statistical Package for the Social Sciences) Statistical Software (version 20.0).

In the evaluation of data, alongside the descriptive statistical methods (Mean, Std. Error, Std. Deviation, Variance, Range, Min., Max., Sum, Skewness, and Kurtosis), the dispersion of the variables was checked using the Shapiro-Wilk normality test. The Cronbach Alpha values were calculated to measure the reliability of the questions constituting the questionnaire. The Pearson Correlation Test was used to test the hypotheses and obtain the relationship among the questions. Linear regression analysis methods were used to identify the related question groups. The results were evaluated in level of significance $p<0.05$. Furthermore, a multivariate regression analysis and mediation analysis were conducted to test the relationships between the question groups.

CHAPTER 4

RESULTS

4.1 Introduction

This chapter presents the results of the questionnaire and the analysis based on the gathered data. The questionnaire results are presented in four parts following the order of the questions: corporate information, awareness about circularity, circular strategies used in the supply chains, and circular methods used in construction steps and digital technologies. Afterwards, four hypotheses are presented and tested through statistical analysis methods. The four question groups are presented in the table below.

Table 4.1. Overview of the Question Groups

Groups	Question Topics
Corporate Information	Type of Staff
	Education of Staff
Awareness About Circularity	Negative environmental effects of construction
	Efforts for sustainability
	Sustainability of CSC's
	Knowledge on Circularity
	Benefits of Circularity
Circular Strategies in Company Operations	Circular Business Model Supply Chain Processes
	ReSOLVE Framework
	10 R Strategy
Circular Methods Used in Construction Steps	Design Phase
	Manufacturing and Construction Phase
	Operation and Maintenance Phase
	End-of-Life Phase
	Digital Technologies

4.2 Reliability of the Questionnaire

One of the most popular methods to measure reliability is the Cronbach Alpha Coefficient. The Cronbach Alpha Coefficient is a value between 0 and 1 and is expected to be greater than 0.7 to achieve desired reliability. Since the questionnaire is based on a 1-5 Likert scale, this method is appropriate to measure the reliability of the questions. The table below presents the classification of the reliability degree according to the Cronbach Alpha Coefficient.

Table 4.2. Cronbach Alpha Value Intervals and Reliability

The Cronbach Alpha Value	**Degree of Reliability**
≥ 0.9	Excellent
$0.7 \leq \alpha < 0.9$	Good
$0.6 \leq \alpha < 0.7$	Acceptable
$0.5 \leq \alpha < 0.6$	Poor
$\alpha < 0.5$	Unacceptable

The SPSS software was used to analyze the Cronbach Alpha Coefficient value of the questions. The reliability coefficient Cronbach's Alpha value is 0.923 for the question group "Awareness About Circularity," 0.924 for the question group "Circular Strategies in Company Operations," 0.942 for the question group "Circular Methods Used in Construction Steps" and 0.956 for all question groups combined.

Table 4.3. Cronbach Alpha Values of the Question Groups

Question Group	**Alfa Cronbach Value**
Awareness About Circularity	0.923
Circular Strategies in Company Operations	0.924
Circular Methods Used in Construction Steps	0.942
All Questions Together	0.956

Cronbach's Alpha value must be over 0.700 for desired reliability. Therefore, all values are sufficient in terms of reliability.

4.3 Corporate Information (CI)

In the first part of the questionnaire, three questions are presented, each comprising four sub-questions. The first question includes four sub-questions about the respondent's personal information. For confidentiality purposes, these questions are excluded from the research. The second question investigates the types of staff working in the respondent companies are being investigated, whereas the third question investigates the level of education of the staff. To present the qualifications of the staff, administrative staff, and technical staff are presented under "Technical Staff," and the non-technical staff and other staff are presented under "Non-Technical Staff." To measure the staff's level of education, undergraduate staff, graduate staff, and PhD staff are presented under "Educated Staff," and other staff are presented under "Uneducated Staff." The groupings that are done for the analysis are explained in the table below.

Table 4.4. Groupings of Staff for the Analyses

<table>
<tr><td rowspan="4">Type of Staff</td><td>Administrative Staff</td><td>4%</td><td rowspan="2">Technical Staff</td><td rowspan="2">25%</td></tr>
<tr><td>Technical Staff</td><td>21%</td></tr>
<tr><td>Non-Technical Staff</td><td>67%</td><td rowspan="2">Non-Technical Staff</td><td rowspan="2">75%</td></tr>
<tr><td>Other</td><td>7%</td></tr>
<tr><td rowspan="4">Education of Staff</td><td>Undergraduate</td><td>24%</td><td rowspan="3">Educated Staff</td><td rowspan="3">28%</td></tr>
<tr><td>Graduate</td><td>4%</td></tr>
<tr><td>PhD</td><td>1%</td></tr>
<tr><td>Other</td><td>72%</td><td>Uneducated Staff</td><td>72%</td></tr>
</table>

Table 4.5. Descriptive Statistics for Corporate Information

Descriptive Statistics		CI Q1.1	CI Q1.2	CI Q1.3	CI Q1.4	CI Q2.1	CI Q2.2	CI Q2.3	CI Q2.4
N		45.00	45.00	45.00	45.00	45.00	45.00	45.00	45.00
Mean		7.09	41.22	133.89	13.38	46.02	7.31	0.69	140.09
%		4.00	21.00	67.00	7.00	24.00	4.00	1.00	72.00
Standard Error		1.66	21.64	76.04	5.38	20.78	3.82	0.46	75.63
Standard Deviation		11.15	145.16	510.07	36.11	139.37	25.61	3.06	507.33
Variance		124.31	21072.09	260174.15	1303.70	19423.48	655.81	9.36	257378.58
Range		49.00	941.00	3206.00	179.00	877.00	150.00	20.00	3200.00
Min.		1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.		50.00	941.00	3206.00	179.00	877.00	150.00	20.00	3200.00
Sum		319.00	1855.00	6025.00	602.00	2071.00	329.00	31.00	6304.00
Skewness	Statistic	2.42	5.78	5.42	3.26	5.28	4.90	6.04	5.44
	Std. Error	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Kurtosis	Statistic	5.61	35.50	31.59	10.95	30.31	24.72	38.28	31.78
	Std. Error	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69

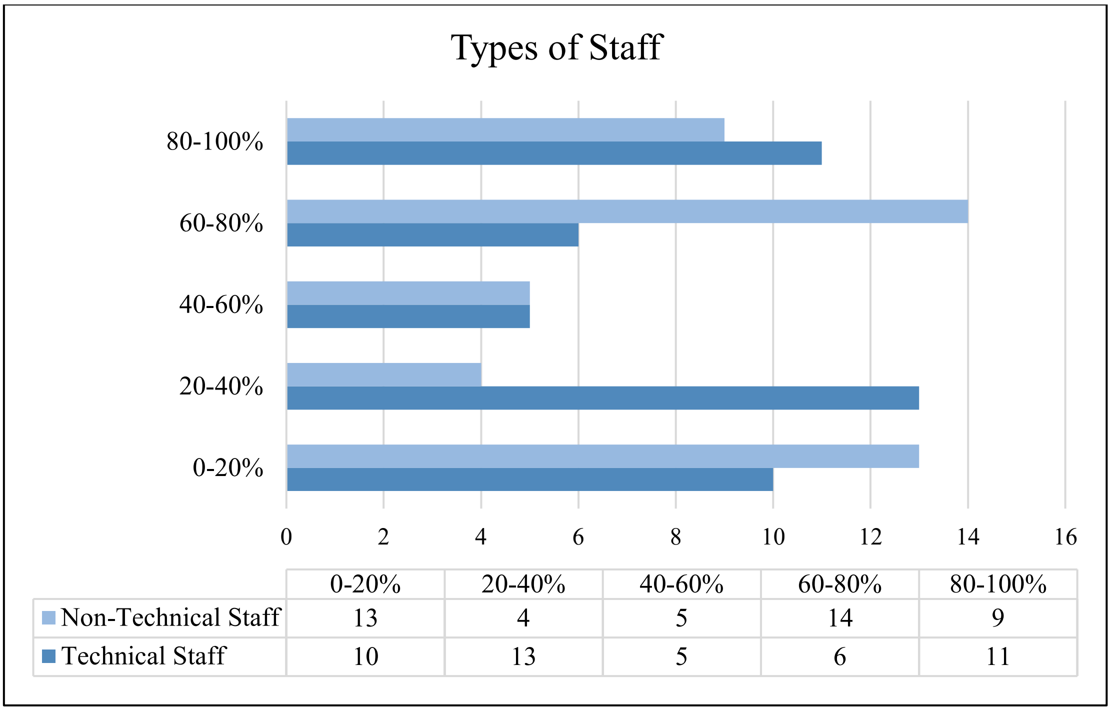


Figure 4.1. Types of Staff

The figure above presents the technical and non-technical staff percentages. As can be interpreted from this analysis, the ratio of non-technical staff to the total amount of staff is 0-20% for thirteen companies, 20-40% for four companies, 40-60% for five companies, 60-80% for fourteen companies, and 80-100% for nine companies.

The ratio of technical staff to the total amount of staff is 0-20% for ten companies, 20-40% for thirteen companies, 40-60% for five companies, 60-80% for six companies, and 80-100% for eleven companies.

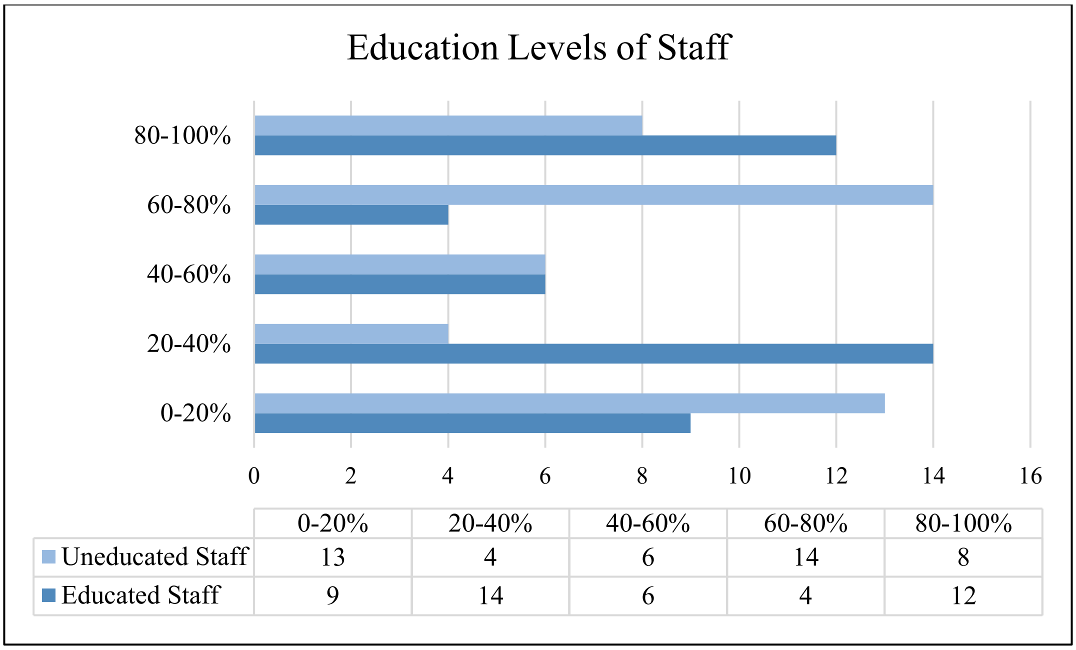


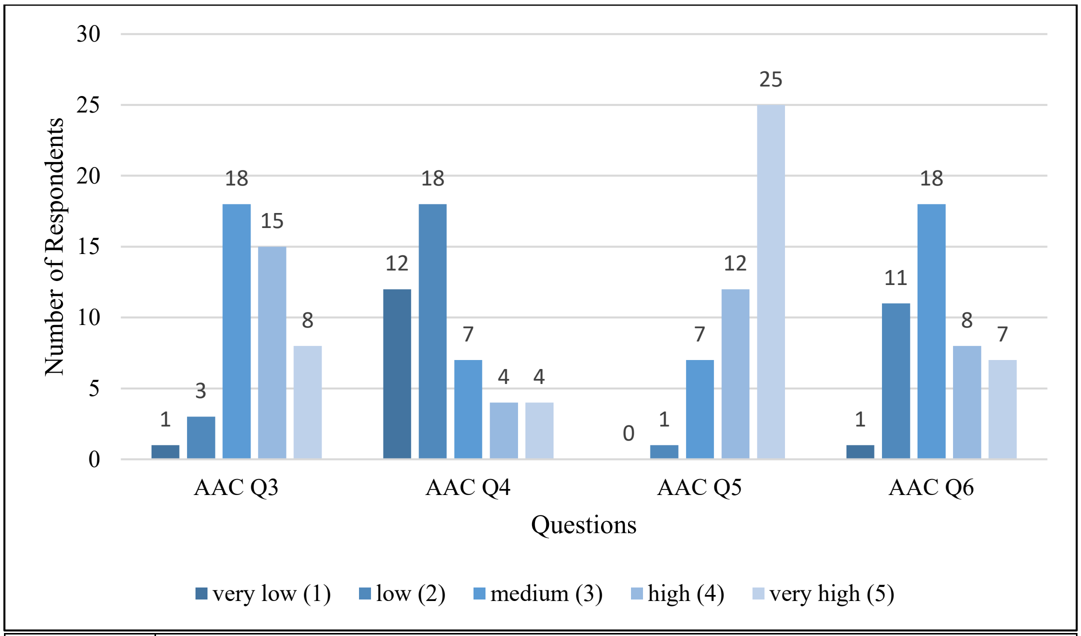
Figure 4.2. Education Level of Staff

The figure above presents the level of education of staff. As can be interpreted from this analysis, 13 companies have a ratio of uneducated staff to the total amount of staff of 0-20%. Four companies have a ratio of uneducated staff to the total amount of staff of 20-40%. Six companies have a ratio of uneducated staff respective to the total amount of staff of 40-60%. Fourteen companies have a ratio of uneducated staff respective to the total amount of staff of 60-80%. Finally, eight companies have a ratio of uneducated staff to total staff of 80-100%.

Nine companies have a ratio of educated staff respective to the total amount of staff of 0-20%. Fourteen companies have a ratio of educated staff respective to the total amount of staff of 20-40%. Six companies have a ratio of educated staff respective to the total amount of staff of 40-60%. Four companies have a ratio of educated staff respective to the total amount of staff of 60-80%. Finally, 12 companies have a ratio of educated staff respective to the total amount of staff of 80-100%.

4.4 Awareness About Circularity (AAC)

The second part of the questionnaire includes five questions in total. These questions investigate the respondents' level of awareness of the concept of circularity. The first four questions concern the concept of circularity and its relationship with sustainability and the construction sector. The fifth question asks the respondents to rate the benefits of circularity. All questions are based on a Likert scale from 1 to 5 (1= very low, 5= very high).



AAC Q3	How much do you think the construction industry contributes negatively to environmental factors such as climate change, carbon dioxide emissions, and material waste today?
AAC Q4	How much effort do you think the construction industry in our country is making to eliminate the problems described above?
AAC Q5	How necessary is it to make construction supply chains more sustainable?
AAC Q6	How much do you know about the concept of circularity and how this concept can be integrated into the construction industry?

Figure 4.3. Awareness About Circularity and Question Descriptions

Table 4.6. Descriptive Statistics for Awareness About Circularity

Descriptive Statistics		AAC Q3	AAC Q4	AAC Q5	AAC Q6	Environmental Factors	Economic Factors	Social Factors
N		45.00	45.00	45.00	45.00	45.00	45.00	45.00
Mean		3.58	2.33	4.36	3.20	3.95	3.54	3.39
Standard Error		0.14	0.18	0.12	0.16	0.11	0.15	0.14
Standard Deviation		0.94	1.23	0.83	1.06	0.76	1.00	0.93
Variance		0.89	1.50	0.69	1.12	0.57	1.01	0.87
Range		4.00	4.00	3.00	4.00	3.00	3.67	3.38
Min.		1.00	1.00	2.00	1.00	2.00	1.33	1.63
Max.		5.00	5.00	5.00	5.00	5.00	5.00	5.00
Sum		161.00	105.00	196.00	144.00	177.83	159.17	152.63
Skewness	Statistic	-0.23	0.87	-1.01	0.30	-0.69	-0.17	0.10
	Std. Error	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Kurtosis	Statistic	0.03	-0.05	0.01	-0.65	0.02	-0.62	-0.69
	Std. Error	0.69	0.69	0.69	0.69	0.69	0.69	0.69

In the first question of this part (AAC Q3), the respondents were asked to state how much they think the construction industry contributes negatively to environmental factors such as climate change, carbon dioxide emissions, and material waste. One company (2.2%) marked very low, three companies (6.7%) marked low, 18 companies marked medium (40%), 15 companies marked high (33.3%), and eight companies marked very high (17.7%). Most respondents think construction's negative effects on environmental factors are medium to very high.

In the second question of this part (AAC Q4), the respondents were asked how much effort they think the construction industry in our country is making to eliminate the adverse effects of the industry on the environment. 12 companies (26.7%) marked very low, 18 companies (40%) marked low, seven companies (15.5%) marked medium, four companies (8.9 %) marked high, and four companies (8.9%) marked very high. The majority of the respondents think that the construction industry is making very low to low effort to eliminate the adverse effects of construction on the environment in our country.

In the third question of this part (AAC Q5), the respondents were asked to state how necessary it is to make construction supply chains more sustainable. None of the companies marked very low, one company (2.2%) marked low, seven companies (15.5%) marked medium, 12 companies (26.7%) marked high, and 25 companies (55.6%) marked very high. The majority of the respondents think that the rate of necessity to make construction supply chains more sustainable is high to very high.

In the fourth question of this part (AAC Q6), the respondents were asked to state their knowledge of the concept of circularity and how it can be integrated into the construction industry. One company (2.2%) marked very low, 11 companies (24.4%) marked low, 18 companies (40%) marked medium, eight companies (17.7%) marked high, and seven companies (15.5%) marked very high. The majority of the respondents have medium knowledge of the concept of circularity.

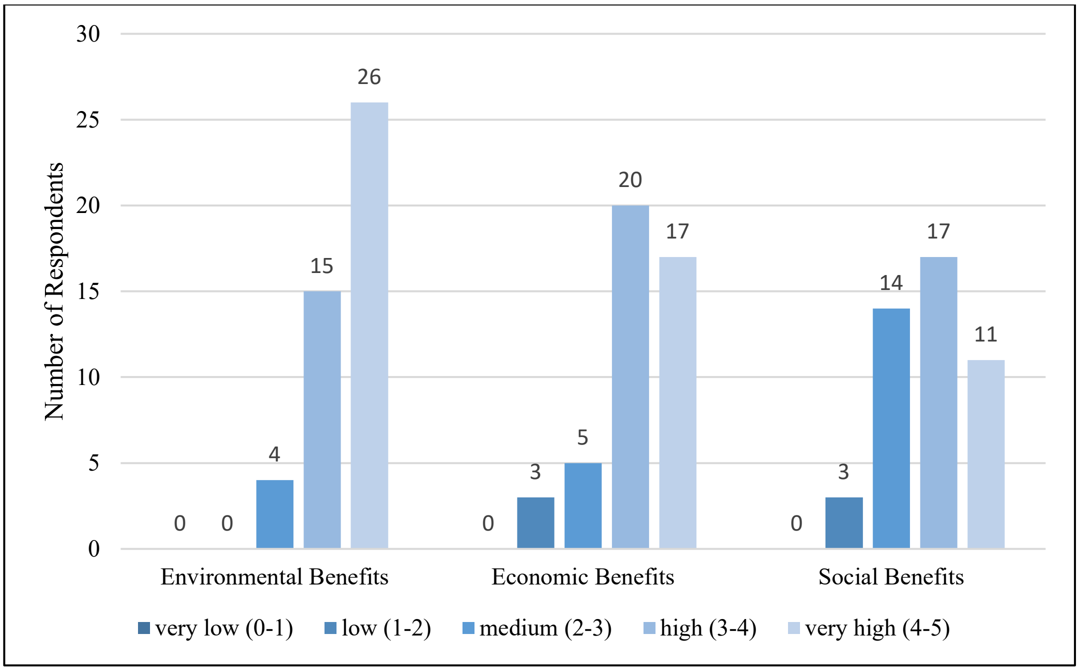


Figure 4.4. Awareness About the Benefits of Circularity

The fifth question in this part (AAC Q7) asked the respondents to mark the effects of a circular construction supply chain on the listed benefits in the question. Twenty-one benefits are listed in the question, and these benefits are grouped into three categories: environmental benefits (including six benefits), economic benefits (including six benefits), and social benefits (including nine benefits). The average value of the marks given to the benefits in each group was calculated and analyzed according to the legend in the table. For the environmental benefits, no company marked very low or low, four companies (8.9%) marked medium, 15 companies (33.3%) marked high, and 26 companies (57.8%) marked very high. For the economic benefits, no company marked very low, three companies (6.7%) marked low, five companies (11.1%) marked medium, 20 companies (44.4%) marked high, and 17 companies (37.8 %) marked very high. For the social benefits, no company marked very low, three companies (6.7%) marked low, 14 companies (31.1%) marked medium, 17 companies (37.8%) marked high, and 11 companies (24.4%) marked very high.

Table 4.7. Percentages of the Responses for Awareness About Circularity

<table>
<tr><th colspan="2">Questions/Percentages</th><th>very low (1)</th><th>low (2)</th><th>medium (3)</th><th>high (4)</th><th>very high (4)</th></tr>
<tr><td colspan="2">AAC Q3</td><td>2.2%</td><td>6.7%</td><td>40%</td><td>33.3%</td><td>17.7%</td></tr>
<tr><td colspan="2">AAC Q4</td><td>26.7%</td><td>40%</td><td>15.5%</td><td>8.9%</td><td>8.9%</td></tr>
<tr><td colspan="2">AAC Q5</td><td>0%</td><td>2.2%</td><td>15.5%</td><td>26.7%</td><td>55.6%</td></tr>
<tr><td colspan="2">AAC Q6</td><td>2.2%</td><td>24.4%</td><td>40%</td><td>17.7%</td><td>15.5%</td></tr>
<tr><td rowspan="3">AAC Q7</td><td>Environmental Benefits</td><td>0%</td><td>0%</td><td>8.9%</td><td>33.3%</td><td>57.8%</td></tr>
<tr><td>Economic Benefits</td><td>0%</td><td>6.7%</td><td>11.1%</td><td>44.4%</td><td>37.8%</td></tr>
<tr><td>Social Benefits</td><td>0%</td><td>6.7%</td><td>31.1%</td><td>37.8%</td><td>24.4%</td></tr>
</table>

The average of the marks given to the level of effects is 3.95/5 for the environmental benefits, 3.56/5 for the economic benefits, and 3.45/5 for the social benefits. Therefore, we can conclude from the responses to this question that according to the respondents, the rating of the level of effects of the listed benefits are as follows:

Environmental Benefits > Economic Benefits > Social Benefits

Table 4.8. Average Scores of Benefits

Benefits		**Average (Out of 5)**	
Environmental Factors	Decreasing the need for primary production through secondary production	3.68	3.95
	Using fewer resources and increasing efficiency	4.24	
	Reducing greenhouse gas emissions	3.66	
	Material savings and recycling	4.06	
	Decreasing of waste	3.97	
	Protection of natural resources	4.06	
Economic Factors	Decreasing of costs	3.62	3.56
	Creation of value	3.71	
	Enhanced resource security	3.77	
	Increasing profits	3.24	
	Balancing price volatility	3.31	
	Reducing the dependency on imports	3.71	
Social Factors	Advanced social rights and human rights	3.44	3.45
	Creation of new job opportunities	3.51	
	Social equity	2.93	
	Sharing economy	3.37	
	Participation and democracy	3.02	
	Health and safety of workers	3.73	
	Increased benefits to customers	3.73	
	Engaged employees	3.37	
	Eco-development	3.97	

4.5 Circular Strategies in Company Operations (CSCO)

The third part of the questionnaire included three questions investigating the level of use of three circular strategies in company operations, "Circular Business Model Supply Chain Processes," "ReSOLVE Framework," and "10R Strategy," in 3 respective questions. All questions are based on a Likert scale from 1 to 5 (1= very low, 5= very high).

Table 4.9. List of Circular Strategies and their Subheadings

Strategy	Subheadings
Circular Business Model Supply Chain Processes	Plan
	Source
	Make
	Deliver
	Use
	Return
	Recover
ReSOLVE Framework	Regenerate
	Share
	Optimize
	Virtualize
	Exchange
10 R Strategy	Refuse
	Rethink
	Reduce
	Reuse
	Repair
	Refurbish
	Remanufacture
	Repurpose
	Recycle
	Recover

Table 4.10. Descriptive Statistics for Circular Strategies in Company Operations

Descriptive Statistics		CSCO Q8 Total	CSCO Q9 Total	Smarter product use and production	Extending the life of the product and its parts	Useful application of materials	CSCO Total
N		45.00	45.00	45.00	44.00	45.00	44.00
Mean		3.52	3.46	3.56	3.62	3.17	3.47
Standard Error		0.14	0.13	0.12	0.13	0.15	0.11
Standard Deviation		0.94	0.84	0.80	0.84	1.02	0.71
Variance		0.88	0.71	0.64	0.71	1.05	0.51
Range		3.86	3.17	3.00	3.20	4.00	3.11
Min.		1.14	1.83	2.00	1.80	1.00	1.89
Max.		5.00	5.00	5.00	5.00	5.00	5.00
Sum		158.57	155.83	160.33	159.40	142.67	152.85
Skewness	Statistic	-0.45	0.21	0.04	-0.05	0.09	0.16
	Std. Error	0.35	0.35	0.35	0.35	0.35	0.36
Kurtosis	Statistic	-0.09	-0.54	-0.55	-1.00	-0.64	-0.11
	Std. Error	0.69	0.69	0.69	0.70	0.69	0.70

Circular Business Model Supply Chain Processes

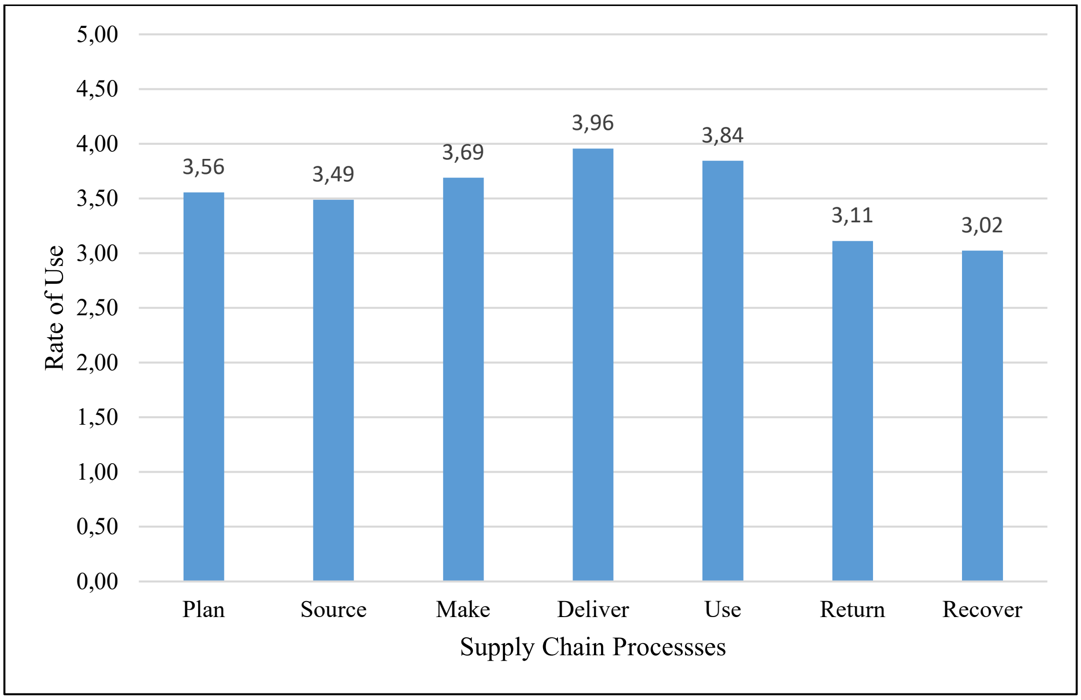


Figure 4.5. Use of Circular Business Model Supply Chain Processes

The first question in this part (CSCO Q8) asks the respondents to mark their rate of usage of circular strategies in their business model supply chain processes: “Plan,” “Source,” “Make,” “Deliver,” “Use,” “Return,” and “Recover.” The average rate of use is 3.55/5 for Plan, 3.48/5 for Source, 3.68/5 for Make, 3.95/5 for Deliver, 3.84/5 for Use, 3.11% for Return, and 3.02 for Recover. It can be seen from the figure that although the results are very similar, the phase in which the respondents use circular strategies the most is the Deliver phase. According to the results, the level of usage of circular strategies in the supply chain models is as follows:

Deliver>Use>Make>Plan>Source>Return>Recover

ReSOLVE Framework

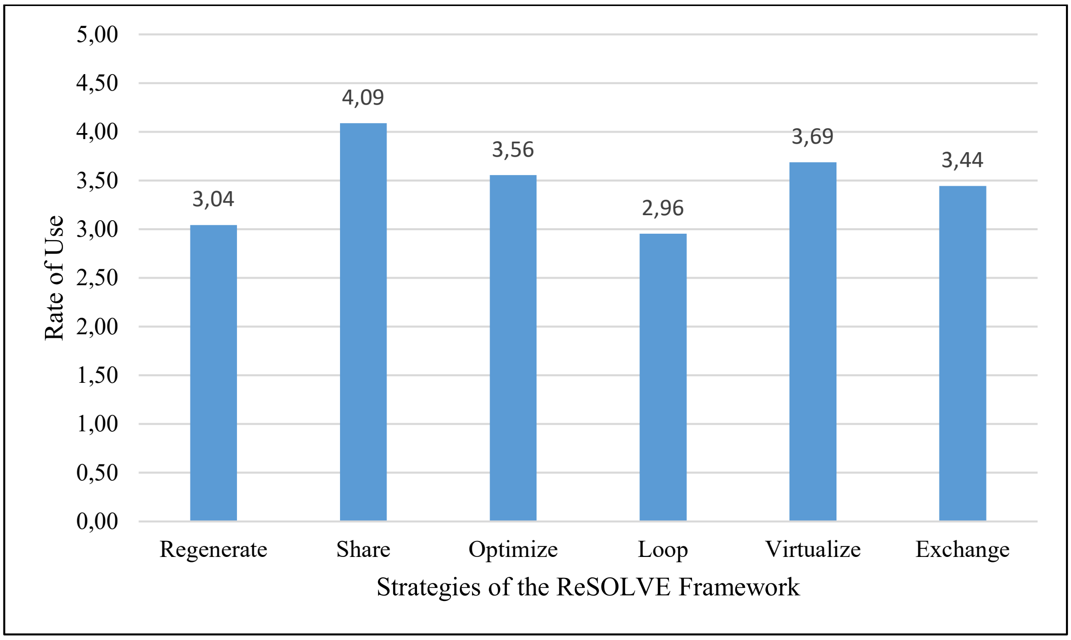


Figure 4.6. Level of Use of the ReSOLVE Framework

The second question in this part of the questionnaire (CSCO Q9) asks the respondents to mark their use of the subheadings of the ReSOLVE Framework. The ReSOLVE Framework constitutes six strategies: "Regenerate," "Share," "Optimize," "Loop," "Virtualize," and "Exchange." The average rate of use is 3.04/5 for Regenerate, 4.08/5 for Share, 3.55/5 for Optimize, 2.95/5 for Loop, 3.68/5 for Virtualize, and 3.44/5 for Exchange.

As can be seen from the figure, although the results are similar, the most used strategy of the ReSOLVE framework is "Share." According to the results, the level of usage of the subheadings of the ReSOLVE framework is as follows:

Share>Virtualize>Optimize>Exchange>Regenerate>Loop

10R Strategy

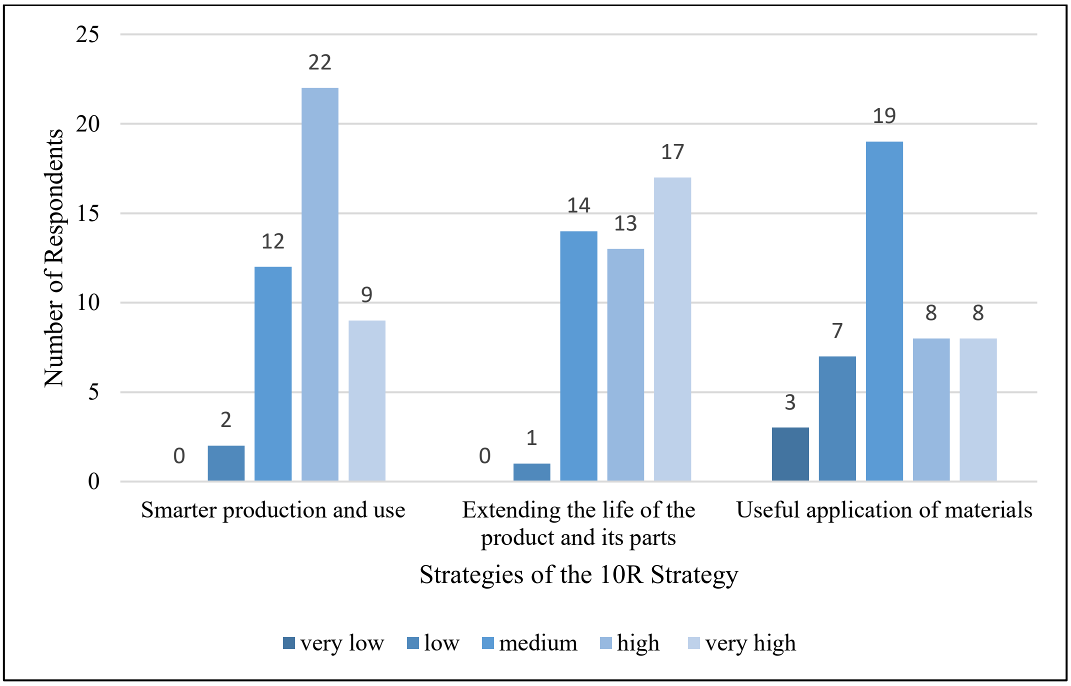


Figure 4.7. Level of Use of the 10R Strategy

The third question in this part (CSCO Q10) asks the respondents to mark their level of usage of the 10R Strategy in their company operations. The 10R Strategy comprises ten strategies grouped within three subheadings: “Smarter production and use,” “Extending the life of the product and its parts,” and “Useful application of materials.” For the use of smarter production and use, no company marked very low, two companies (4.4%) marked low, 12 companies (26.7%) marked medium, 22 companies (48.9%) marked high, and nine companies (20%) marked very high. For the use of useful application of materials, no company marked very low, one company (2.2%) marked low, 14 companies (31.1%) marked medium, 13 companies (28.9%) marked high, and 17 companies (37.8%) marked very high. For the use of useful application and materials, three companies (6.7%) marked very low, seven companies marked low (15.5%), 19 companies (42.2%) marked medium, eight companies (17.8%) marked high, and eight companies (17.8%) marked very high.

The average of the marks given to the use of strategies is 3.56/5 for "Smarter production and use," 3.62/5 for "Extending the life of the product and its parts," and 3.07/5 for "Useful application of materials." Therefore, we can conclude from the responses to this question that according to the respondents, the rating of the level of effects of the listed benefits are as follows:

Extending the life of the product and its parts>Smarter production and use>Useful application of materials

Table 4.11. Breakdown of the 10R Strategy

Steps		**Average (Out of 5)**	
Aim	**Strategy**		
Smarter product use and production	Refuse	3.24	3.56
	Rethink	3.82	
	Reduce	3.62	
Extending the life of the product and its parts	Reuse	3.84	3.62
	Repair	3.86	
	Refurbish	3.68	
	Remanufacture	3.40	
	Repurpose	3.35	
Useful application of materials	Recycle	3.24	3.07
	Recover	2.91	

Although the results are very close to each other, within the strategies that constitute the 10R Strategy, the Repair strategy is the most used among the respondents. The level of use of the strategies is as follows:

Repair>Reuse>Rethink>Refurbish>Reduce>Repurpose>Refuse=Recycle>Recover

Table 4.12. Percentages of the Responses to Circular Strategies Used in Company Operations

Strategy	Subheadings	Percentages				
		very low(1)	low(2)	medium(3)	high(4)	very high(5)
Circular Business Model Supply Chain Processes	Plan	5%	11%	33%	27%	24%
	Source	7%	20%	16%	33%	24%
	Make	4%	16%	16%	36%	28%
	Deliver	2%	4%	22%	38%	33%
	Use	7%	7%	18%	33%	35%
	Return	13%	22%	27%	16%	22%
	Recover	20%	13%	27%	24%	16%
ReSOLVE Framework	Regenerate	11%	20%	36%	20%	13%
	Share	0%	13%	9%	33%	45%
	Optimize	7%	11%	27%	31%	24%
	Loop	16%	24%	27%	16%	17%
	Virtualize	0%	13%	29%	33%	25%
	Exchange	5%	20%	27%	24%	24%
10 R Strategy	Refuse	2%	27%	29%	29%	13%
	Rethink	0%	8%	27%	38%	27%
	Reduce	2%	16%	27%	28%	27%
	Reuse	2%	11%	22%	29%	36%
	Repair	0%	9%	29%	29%	33%
	Refurbish	4%	16%	16%	36%	28%
	Remanufacture	9%	18%	24%	22%	27%
	Repurpose	11%	13%	25%	31%	20%
	Recycle	11%	16%	31%	22%	20%
	Recover	15%	27%	27%	13%	18%

4.6 Circular Methods Used in Construction Steps (CMUCS)

The fourth part of the questionnaire includes five questions in total. The first four questions investigate the usage level of the given circular methods in four consequent steps of a construction supply chain: design, manufacturing and construction, operation and maintenance, and end-of-life, respectively. The fifth question investigates the level of usage of the seven given digital technologies to achieve circularity in construction supply chains. All questions are based on a Likert scale from 1 to 5 (1= very low, 5= very high). The use of phase-specific methods is presented with bar charts and tables for each respective phase, along with percentages and average use scores.

Furthermore, the respondents give some examples of using phase-specific circular methods. These examples from the Turkish construction industry are presented under each respective construction phase. Then, the respondent companies are put under three categories according to the type of projects they conduct: infrastructure, infrastructure + superstructure, and superstructure. The use of phase-specific circular methods is examined according to these three categories.

Table 4.13. Descriptive Statistics for Circular Methods Used in Construction Steps

Descriptive Statistics		CMUCS Q11 Total	CMUCS Q12 Total	CMUCS Q13 Total	CMUCS Q14 Total	CMUCS Q15 Total
N		45.00	45.00	45.00	45.00	45.00
Mean		2.92	2.71	3.33	2.93	2.35
Standard Error		0.14	0.14	0.13	0.15	0.15
Standard Deviation		0.96	0.93	0.89	1.00	1.00
Variance		0.92	0.86	0.78	1.01	1.01
Range		4.00	4.00	4.00	4.00	4.00
Min.		1.00	1.00	1.00	1.00	1.00
Max.		5.00	5.00	5.00	5.00	5.00
Sum		131.33	122.17	150.00	131.67	105.57
Skewness	Statistic	-0.10	0.30	0.07	0.16	0.828
	Std. Error	0.35	0.35	0.35	0.35	0.354
Kurtosis	Statistic	-0.14	0.10	0.15	-0.42	0.465
	Std. Error	0.69	0.69	0.69	0.69	0.695

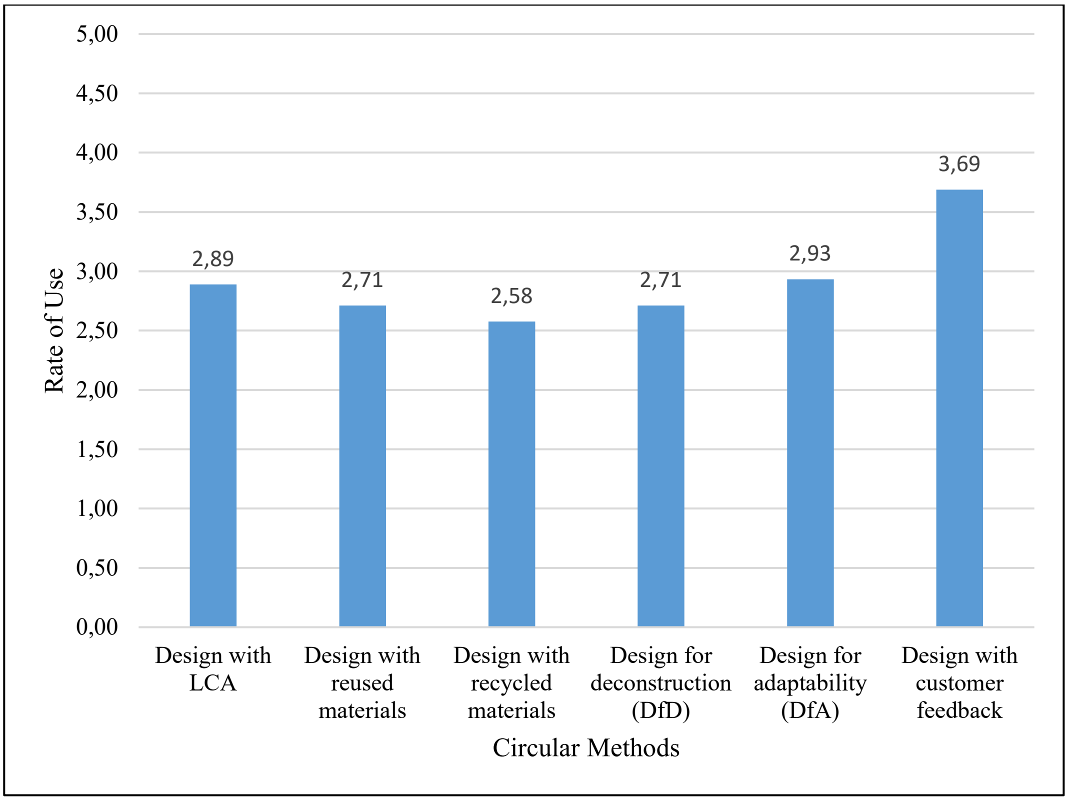


Figure 4.8. Circular Methods Used in the Design Phase

The first question in this part (CMUCS Q11) investigates the level of use of the six given circular methods in the design phase of the construction supply chain. The average rate of use of the circular methods is 2.88/5 for "Design with LCA," 2.71/5 for "Design with reused materials," 2.57/5 for "Design with recycled materials," 2.71/5 for "Design for deconstruction," 2.71/5 for "Design for adaptability," 3.68/5 for "Design with customer feedback." Therefore, we can conclude from the responses to this question that according to the respondents, the rating of the use of these circular methods in the design phase is as follows:

Design with customer feedback>Design for adaptability>Design with LCA>Design with reused materials=Design for deconstruction>Design with recycled materials

When asked about the details of the use of the given circular methods in the design phase, some respondents claimed that they use design with LCA to elongate the lifetime of buildings. One respondent claimed that they design with natural ventilation to obtain energy efficiency in the long term as an example of designing with LCA. For designing with reused and recycled materials, one respondent claimed that they reuse AC systems and other mechanical equipment in factory design. Another respondent claimed they used a unique material with 95% waste wood and recycled polymer for decking, and laminate hardwood parquets from recycled sawdust. For designing for deconstruction and adaptability, two respondents claimed that they design and construct prefabricated buildings and tiny houses that allow for deconstruction, and one respondent claimed that they integrate partial walls into houses to allow for adaptability. Furthermore, designing with customer feedback is the most used method in the design phase.

Table 4.14. Examples of Respondents for Circular Methods in the Design Phase

Design with LCA	• Used to elongate the lifetime of buildings • Design with natural ventilation to obtain energy efficiency in the long term
Design with reused materials	• AC systems and other mechanical equipment in factory design
Design with recycled materials	• Decking with 95% waste wood and recycled polymer • Laminate hardwood parquets from recycled sawdust
Design for deconstruction	• Prefabricated buildings • Tiny houses
Design for adaptability	• Partial walls for adaptable houses
Design with customer feedback	• The most used method in the design phase

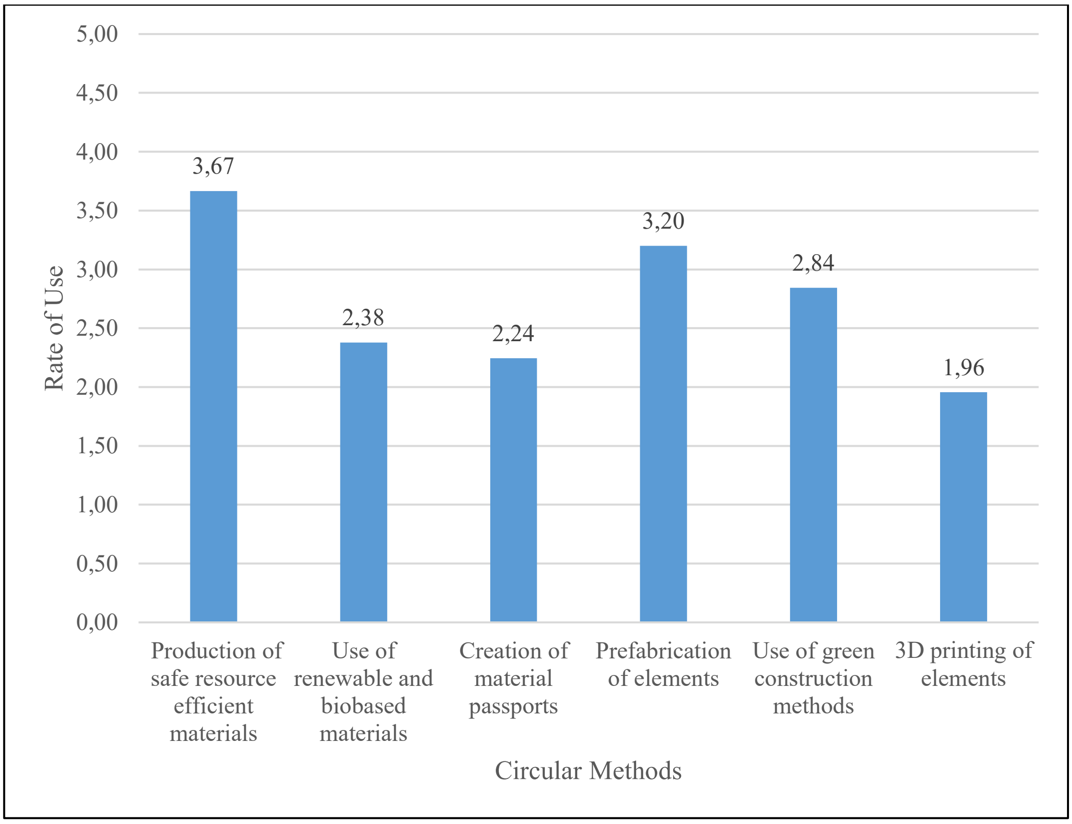


Figure 4.9. Circular Methods Used in the Manufacturing and Construction Phase

The second question in this part (CMUCS Q12) investigates the level of use of six given circular methods in the manufacturing and construction phase. The average rate of use of the circular methods is 3.66/5 for "Production of safe resource-efficient materials," 2.37/5 for "Use of renewable and biobased materials," 2.24/5 for "Creation of material passports," 3.20/5 for "Prefabrication of elements," 2.84/5 for "Use of green construction methods," and 1.95/5 for "3D printing of elements". Therefore, we can conclude from the responses to this question that according to the respondents, the use of these circular methods in the manufacturing and construction phase are as follows:

Production of safe resource-efficient materials>Prefabrication of elements>Use of green construction methods>Use of renewable and biobased materials>Creation of material passports>3D printing of elements

When asked about the details of using the given circular methods in the manufacturing and construction phase, three respondents claimed that they produce recycled steel as safe and resource-efficient materials. Two respondents claimed that they use laminated hardwood parquets and wooden materials for renewable and biobased materials, whereas five respondents claimed that they prefer rock wool insulation instead of XPS due to its multiple benefits. Six respondents who marked high or very high for the creation of material passports claimed that they have not yet used material passports in their projects; however, they have plans and attempts to use them. For the prefabrication of elements, two respondents claimed that they use precast concrete, whereas one respondent claimed that they prefabricate light steel in their own factory and use the light steel that they produce in their projects. Four respondents contended that they integrate solar panels in their projects and primarily use triple glass windows to obtain energy efficiency as green construction methods. Furthermore, three respondents who marked medium to very high for 3D printing of elements claimed they have attempted to use 3D printing, especially in unique plumbing parts.

Table 4.15. Examples of Respondents for Circular Methods in the Manufacturing and Construction Phase

Production of safe, resource-efficient materials	• Recycled steel
Use of renewable and biobased materials	• Laminate hardwood parquets and wooden materials • Rockwool insulation instead of XPS
Creation of material passports	• Respondents have attempted and planned to use material passports.
Prefabrication of elements	• Precast concrete • Light steel
Use of green construction methods	• Solar panels • Triple glass windows for energy efficiency
3D printing of elements	• Attempts to 3D print unique plumbing parts

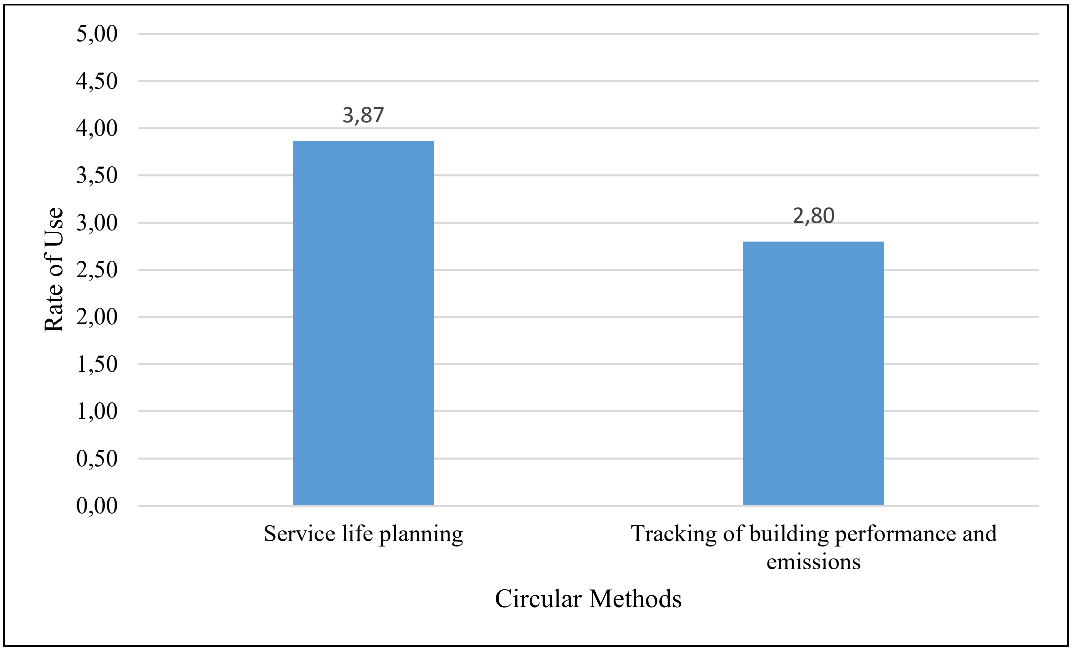


Figure 4.10. Circular Methods used in the Operation and Maintenance Phase

The third question in this part (CMUCS Q13) investigates the level of use of two circular methods in the operation and maintenance phase. The average use rate of circular methods is 3.86/5 for "Service life planning" and 2.80/5 for "Tracking of building performance and emissions." Therefore, we can conclude from the responses to this question that according to the respondents, the rating of the use of these circular methods in the operation and maintenance phase are as follows:

Service life planning>Tracking of building performance and emissions

When asked about the details of the use of the given circular methods in the operation and maintenance phase, five respondents claimed that they use codes and standards for service life planning, whereas two respondents stated that they consider tracking building emissions and performance due to government implications for imposing energy identity cards to buildings.

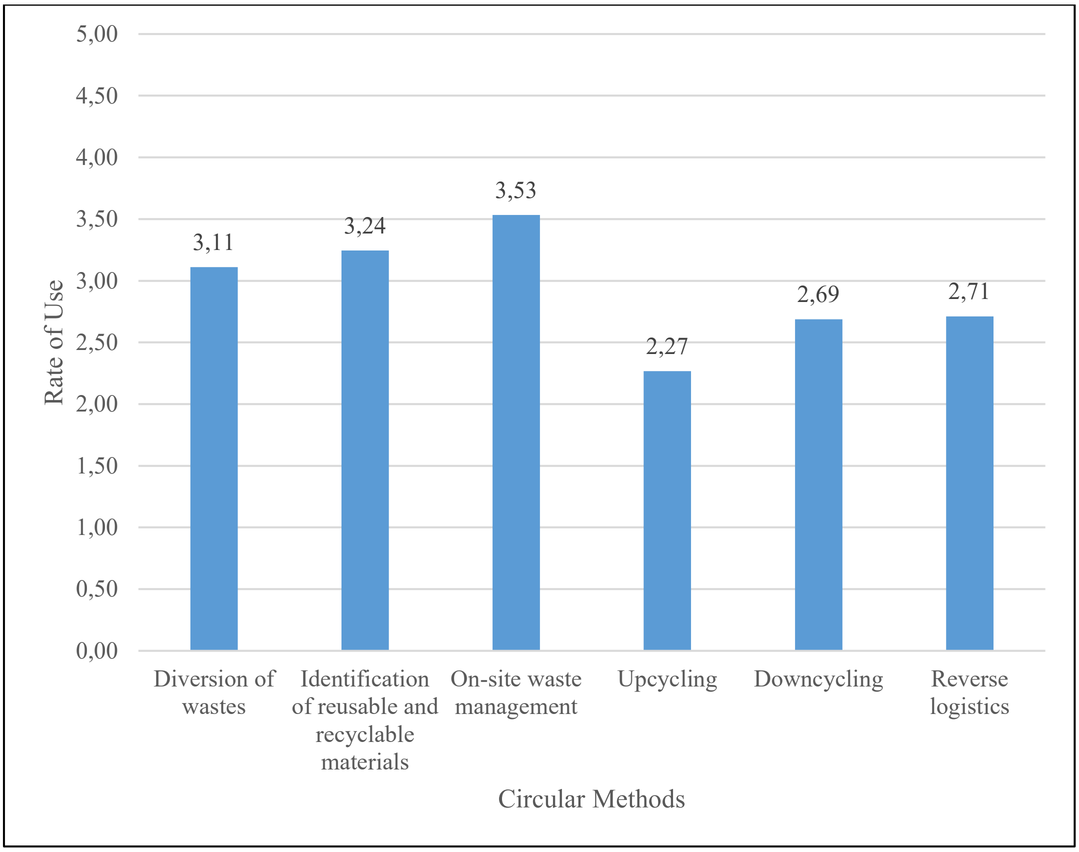


Figure 4.11. Circular Methods Used in the End-of-Life Phase

The fourth question in this part (CMUCS Q14) investigates the level of use of six given circular methods in the end-of-life phase. The average rate of use of the circular techniques is 3.11/5 for "Diversion of wastes," 3.24/5 for "Identification of reusable and recyclable materials," 3.53/5 for "On-site waste management," 2.26/5 for "Upcycling," 2.68/5 for "Downcycling," and 2.71/5 for "Reverse logistics." Therefore, we can conclude from the responses to these questions that according to the respondents, the rating of the use of these circular methods in the end-of-life phase is as follows:

On-site waste management>Identification of reusable and recyclable materials>Diversion of wastes>Reverse logistics>Downcycling>Upcycling

When asked about the details of using the given circular methods in the end-of-life phase, five respondents claimed they sort the wastes to be used in the upcoming projects or entirely disposed of. Five respondents claim they identify reusable and recyclable components for forthcoming projects, such as sanitary ware, metal components, parquets, electrical sockets, and mechanical equipment such as AC units. Five respondents who marked medium to very high for upcycling claimed that they have attempted to use upcycling, whereas three respondents contended that they downcycle materials such as PVC, glass, or material packaging. Furthermore, two respondents contended that they reused material packaging in the previous phases of the supply chain and obtained mechanical equipment at the end-of-life phase to be reused in the earlier stages of the supply chain for reverse logistics.

Table 4.16. Examples of Respondents for Circular Methods in the End-of-Life Phase

Diversion of wastes	• Wastes are sorted to be used of disposed of
Identification of reusable and recyclable components	• Sanitary ware such as sinks • Metal components • Parquets • Electrical sockets • Mechanical equipment
On-site waste management	• The most used circular method in the end-of-life phase
Upcycling	• Attempts for upcycling
Downcycling	• PVC • Glass • Packaging
Reverse logistics	• Reuse of material packaging in the previous stages • Obtaining mechanical equipment at the end-of-life phase to be reused in the earlier stages of the supply chain

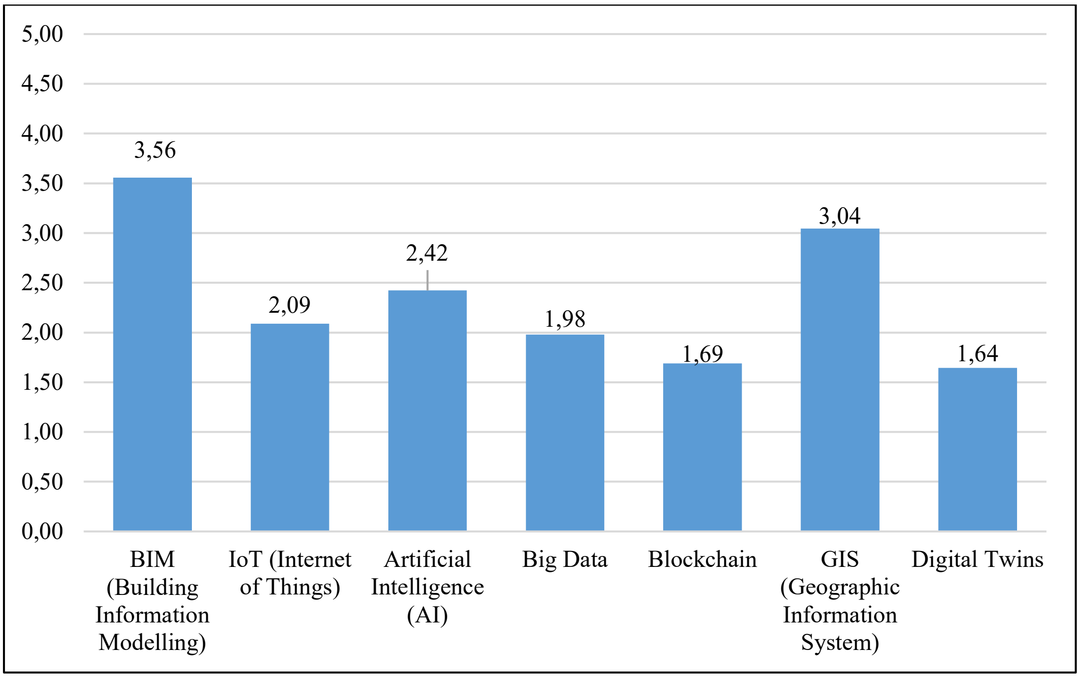


Figure 4.12. Digital Technologies Used in Construction Supply Chains

The fifth question in this part (CMUCS Q15) investigates the level of use of seven given digital technologies throughout the construction supply chain. The average rate of use of digital technologies is 3.55/5 for "BIM," 2.08/5 for "IoT," 2.42/5 for "Artificial Intelligence," 1.97/5 for "Big Data," 1.68/5 for "Blockchain," 3.04/5 for "GIS," and 1.64/5 for "Digital Twins." Therefore, we can conclude from the responses to this question that according to the respondents, the rating of the use of these digital technologies throughout the construction supply chain are as follows:

BIM (Building Information Modelling)>GIS (Geographic Information System)>Artificial Intelligence (AI)>IoT (Internet of Things)>Big Data>Blockchain>Digital Twins

When asked about the details of using the given digital technologies throughout construction supply chains, five respondents claimed that they use BIM to monitor the performance of the design before it is built to ensure cost efficiency. Furthermore, these respondents claimed they use BIM-integrated GIS to obtain accurate geographic data to ensure a smooth project planning process. Three respondents claimed they use AI to ensure customer satisfaction, primarily to save time and workforce. Also, one respondent claimed they have attempted to use blockchain, especially with global partners, to create smart contracts and reliable documentation in the bidding process. Furthermore, five respondents claimed that they have mediocre knowledge of Digital Twins, the Internet of Things, and Big Data. They claimed they have attempted to use these technologies to provide easier processing of large amounts of data, create safe on-site operations, and ensure customer satisfaction by monitoring the project in the early design phases.

Table 4.17. Examples of Respondents for Digital Technologies

Building Information Modelling (BIM)	• To monitor the performance of the design before it is built to ensure cost-efficiency
Internet of Things (IoT)	• Attempts to use to ensure the integrity of equipment and to provide safety for the operators
Artificial Intelligence (AI)	• To ensure customer satisfaction and save time and workforce
Big Data	• Attempts to use to manage large amounts of data gathered from each discipline at each step
Blockchain	• Attempts to use, especially with global partners, to create smart contracts and reliable documentation in the bidding process
Geographical Information System (GIS)	• To obtain accurate geographical data to ensure a smooth project planning process

Table 4.18. Percentages of the Responses to Circular Methods used in Construction Steps and Digital Technologies

Phase	Circular Method	Percentages				
		1	2	3	4	5
Design Phase	Design with LCA	20%	20%	22%	27%	11%
	Design with reused materials	24%	22%	27%	11%	16%
	Design with recycled materials	29%	20%	27%	13%	11%
	Design for deconstruction	27%	18%	20%	29%	5%
	Design for adaptability	22%	9%	34%	24%	11%
	Design with customer feedback	9%	9%	22%	24%	36%
Manufacturing and Construction Phase	Production of safe, resource-efficient materials	7%	11%	20%	33%	29%
	Use of renewable and biobased materials	31%	24%	27%	11%	7%
	Creation of material passports	44%	11%	24%	16%	4%
	Prefabrication of elements	13%	13%	31%	24%	18%
	Use of green construction methods	20%	18%	29%	24%	9%
	3D printing of elements	58%	13%	11%	11%	7%
Operation and Maintenance Phase	Service life planning	2%	2%	36%	27%	33%
	Tracking of building performance and emissions	13%	29%	31%	18%	9%
End-of-Life Phase	Diversion of wastes	13%	18%	29%	24%	16%
	Identification of reusable and recyclable components	11%	11%	36%	27%	16%
	On-site waste management	2%	13%	40%	18%	27%
	Upcycling	40%	13%	31%	11%	4%
	Downcycling	31%	13%	22%	22%	11%
	Reverse logistics	29%	16%	24%	18%	13%
Digital Technologies	BIM	16%	4%	18%	33%	29%
	IoT	51%	18%	11%	11%	9%
	AI	36%	20%	22%	11%	11%
	Big Data	56%	13%	16%	9%	7%
	Blockchain	69%	9%	13%	2%	7%
	GIS	29%	7%	13%	33%	18%
	Digital Twins	64%	18%	11%	2%	4%

(1=very low, 2=low, 3=medium, 4=high, 5=very high)

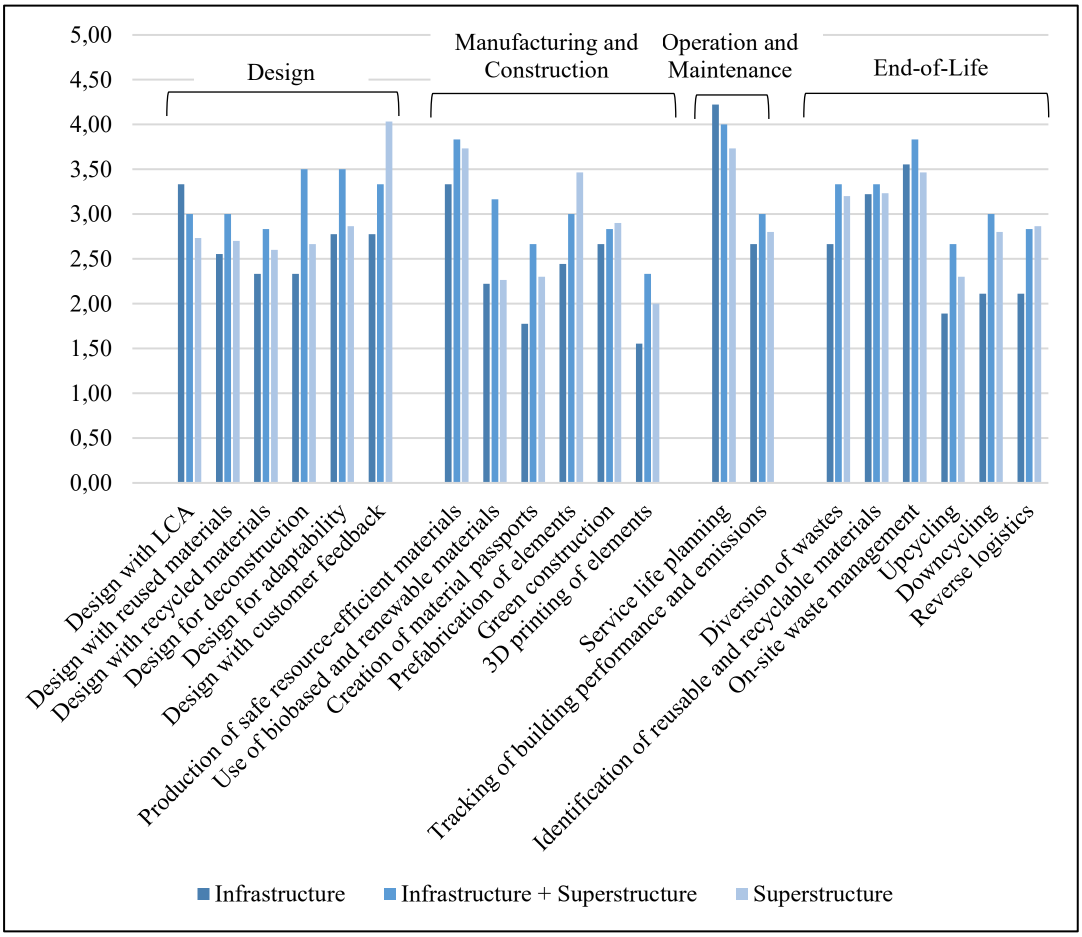
To analyze the use of phase-specific circular methods according to the project types, the respondent companies were grouped under three according to their projects: infrastructure, infrastructure and superstructure, and superstructure. Of the 45 respondent companies that completed the questionnaire, 9 of them focus on projects that are related to infrastructure, 6 of them focus on projects that are related to both infrastructure and superstructure, and 30 of them focus on projects that are related to superstructure.

When companies focusing solely on infrastructure were analyzed, it was found that the circular method most commonly used for the design phase was "Design with LCA." In contrast, the least used circular method is "Design with Recycled Materials." For the manufacturing and construction phase, the circular method that is most commonly used is "Production of Safe Resource-Efficient Materials." In contrast, the circular method that is least frequently used is "3D Printing of Elements." For the operation and maintenance phase, the circular method that is most used is "Service Life Planning." In contrast, the circular method that is least used is "Tracking of Building Performance and Emissions." The most used circular method for the end-of-life phase is "On-Site Waste Management." In contrast, the least used circular method is "Upcycling."

When companies that focus on both infrastructure and superstructure were analyzed, it was found that for the design phase, the most used circular methods are "Design with Deconstruction" and "Design for Adaptability." In contrast, the least used circular method is "Design with Recycled Materials." For the manufacturing and construction phase, the circular method that is used the most is "Production of Safe, Resource Efficient Materials," whereas "3D Printing of Elements" is the circular method that is least used. For the operation and maintenance phase, the circular method that is most used is "Service Life Planning." In contrast, the circular method that is least used is "Tracking of Building Performance and Emissions." For the end-of-life phase, the most used circular method is "On-Site Waste Management," whereas the least used circular method is "Upcycling."

When companies that focus solely on superstructure were analyzed, it was found that the most used circular method for the design phase is "Design with Customer Feedback." In contrast, the least used circular method is "Design with Recycled Materials." For the manufacturing and construction phase, the circular method that is most commonly used is "Production of Safe Resource-Efficient Materials." In contrast, the circular method that is least frequently used is "3D Printing of Elements." For the operation and maintenance phase, the circular method that is most used is "Service Life Planning." In contrast, the circular method that is least used is "Tracking of Building Performance and Emissions." For the end-of-life phase, the most used circular method is "On-Site Waste Management," whereas the least used circular method is "Upcycling."

Figure 4.13. Use of Circular Methods According to Project Types



4.7 Statistical Tests of the Questions

Hypothesis I:

Null Hypothesis: There is no relationship between the technicality of staff and their level of education and circular methods used in the construction supply chain steps.
H0: $\rho_{xy} \neq 0$ or $\mu_r \neq 0$.

Alternative Hypothesis: As the technicality of staff and their level of education increases, the circular methods used in the company's construction supply chain steps increase.
HA: $\rho_{xy} = 0$ or $\mu_r = 0$.

The first hypothesis aims to test the relationship between the technicality of staff members and their level of education and the circular methods used in the construction supply chain steps.

Table 4.19. Pearson Correlation Test for Hypothesis I

		Circular Methods Use in Construction Steps
Corporate Information	**r**	-0.143
	p	0.350
	N	45

No correlation between "Circular Methods Used in Construction Steps" and "Corporate Information" has been observed (r=-0.143, p=0.350). According to the Pearson Correlation Test results, the "Null Hypothesis" was accepted for Hypothesis I. There is no relationship between the technicality of staff members and their level of education and the circular methods used in the construction supply chain steps.

Table 4.20. Linear Regression Analysis for Hypothesis I

Model	**R**	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**		
1	0.143	0.02	-0.002	0.84148		
	Change Statistics					
	R Square Change	**F Change**	**df1**	**df2**	**p**	
	0.02	0.895	1	44	0.350	
a	Predictors: (Constant). Corporate Information					
b	Dependent Variable: Circular Methods Use in Construction Steps					

Table 4.21. Coefficients for Hypothesis I

	Unstandardized Coefficients		**Standardized Coefficients**	**t**	**p**
	B	**Std. Error**	**Beta**		
Corporate Information	-0,04	0,04	-0,143	-0,95	0,350
Dependent Variable: Circular Methods Use in Construction Steps					

Linear Regression Analysis was conducted on the relationship between "Corporate Information" and "Circular Methods Used in Construction Steps," which was not statistically meaningful in the Pearson Correlation Test. In the linear regression analysis, the relationship between these two question groups was not statistically meaningful. The R^2 value is 2%, while the Adjusted R^2 is 0.2%.

Hypothesis II:

Null Hypothesis: There is no relationship between the awareness about circularity and circular methods used in the steps of the construction supply chain.

H0: $\rho_{xy} \neq 0$ or $\mu_r \neq 0$.

Alternative Hypothesis: As the awareness about circularity increases, the circular methods used in the steps of the construction supply chain increase.

HA: $\rho_{xy} = 0$ or $\mu_r = 0$.

The second hypothesis aims to test the relationship between the awareness about circularity and circular methods used in the steps of the construction supply chain.

Table 4.22. Pearson Correlation Test for Hypothesis II

		Circular Methods Used in Construction Steps
Awareness About Circularity	**r**	0.319
	p	0.033
	N	45

A positive, meaningful correlation between "Circular Methods Used in Construction Steps" and "Awareness About Circularity" was observed (r=0.319 p=0.033). Given the Pearson Correlation Test results presented above, the "Alternative Hypothesis" was accepted for Hypothesis II. As the awareness about circularity increases, the circular methods used in the steps of the construction supply chain increase.

Table 4.23. Linear Regression Analysis for Hypothesis II

R	**R Square**	**Adjusted R Square**	**Std. Error of the Estimate**	
0.319	0.102	0.081	0.806	
Change Statistics				
R Square Change	**F Change**	**df1**	**df2**	**p**
0.102	4.87	1	44	0.033
Predictors: (Constant). Awareness About Circularity				
Dependent Variable: Circular Methods Used in Construction Steps				

Table 4.24. Coefficients for Hypothesis II

	Unstandardized Coefficients		**Standardized Coefficients**	**t**	**p**
	B	**Std. Error**	**Beta**		
Awareness About Circularity	0.48	0.22	0.32	2.21	0.033
Dependent Variable: Circular Methods Used in Construction Steps					

Linear Regression Analysis was conducted on the relationship between “Awareness About Circularity” and “Circular Methods Used in Construction Steps,” which was found statistically meaningful in the Pearson Correlation Test. In the Linear Regression Analysis, the relationship between these two question groups was positive and statistically meaningful (p=0.033). The R^2 value is 10%, while the Adjusted R^2 is 8.1%.

Hypothesis III:

Null Hypothesis: There is no relationship between the circular strategies in the overall company operations and the circular methods used in the steps of the construction supply chain.

H0: $\rho_{xy}=0$ or $\mu_r=0$.

Alternative Hypothesis: As the circular strategies in the overall company operations (10R strategy, ReSOLVE framework, Circular Business Model Supply Chain Processes) increase, the circular methods used in the steps of the construction supply chain increase.

HA: $\rho_{xy}\neq0$ or $\mu_r\neq0$.

The third hypothesis tests the relationship between circular strategies in the overall company operations and circular methods used in the construction supply chain steps.

Table 4.25. Pearson Correlation Test for Hypothesis III

		Circular Methods Use in Construction Steps
Circular Strategies in Company Operations	**r**	0.566
	p	0.0001
	N	44

A positive, meaningful correlation between “Circular Methods Used in Construction Steps” and “Circular Strategies in Company Operations” was observed (r=0.566, p=0.0001). Given the Pearson Correlation Test results presented above, the “Alternative Hypothesis” was accepted for Hypothesis III. As the circular strategies in the overall company operations (10R strategy, ReSOLVE framework, Circular Business Model Supply Chain Processes) increase, the circular methods used in the steps of the construction supply chain increase.

Table 4.26. Linear Regression Analysis for Hypothesis III

<table>
<tr><th>R</th><th>R Square</th><th colspan="2">Adjusted R Square</th><th colspan="3">Std. Error of the Estimate</th></tr>
<tr><td>0.566</td><td>0.32</td><td colspan="2">0.304</td><td colspan="3">0.71</td></tr>
<tr><td colspan="7">Change Statistics</td></tr>
<tr><td colspan="3">R Square Change</td><td>F Change</td><td>df1</td><td>df2</td><td>p</td></tr>
<tr><td colspan="3">0.32</td><td>19.80</td><td>1</td><td>44</td><td>0.0001</td></tr>
<tr><td colspan="7">Predictors: (Constant). Circular Strategies in Company Operations</td></tr>
<tr><td colspan="7">Dependent Variable: Circular Methods Use in Construction Steps</td></tr>
</table>

Table 4.27. Coefficients for Hypothesis III

	Unstandardized Coefficients		Standardized Coefficients	t	p
	B	Std. Error	Beta		
Circular Strategies in Company Operations	0.67	0.15	0.57	4.45	0.0001
Dependent Variable: Circular Methods Used in Construction Steps					

Linear Regression Analysis was conducted on the relationship between "Circular Strategies in Company Operations" and "Circular Methods Used in Construction Steps," which was found statistically meaningful in the Pearson Correlation Test. In the Linear Regression Analysis, the relationship between these two question groups was positive and statistically meaningful (p=0.0001). The R^2 value is 32%, while the Adjusted R^2 is 30.4%.

Hypothesis IV:

Null Hypothesis: There is no meaningful relationship between the digital technologies used in construction companies and the circular methods used in the steps of the construction supply chain.

H0: $\rho_{xy} \neq 0$ or $\mu_r \neq 0$.

Alternative Hypothesis: As the amount of digital technologies used in construction companies increases, the circular methods used in the steps of the construction supply chain increase.

HA: $\rho_{xy} = 0$ or $\mu_r = 0$.

The fourth hypothesis aims to test the relationship between the use of seven digital technologies throughout the construction supply chain and circular methods used in the steps of the construction supply chain.

Table 4.28. Pearson Correlation Test for Hypothesis IV

		Circular Methods Used in Construction Steps
Digital Technologies	**r**	0.573
	p	0.0001
	N	45

A meaningful correlation was observed between "Circular Methods Used in Construction Steps" and "Digital Technologies" (r=0.573, p=0.0001). Given the Pearson Correlation Test results presented above, the Alternative Hypothesis was accepted for Hypothesis IV. As the amount of digital technologies used in construction companies increases, the circular methods used in the steps of the construction supply chain increase.

Table 4.29. Linear Regression Analysis for Hypothesis IV

R	R Square	Adjusted R Square	Std. Error of the Estimate	
0.573	0.329	0.313	0.69	
Change Statistics				
R Square Change	**F Change**	**df1**	**df2**	**p**
0.329	21.04	1	44	0.0001
Predictors: (Constant). Digital Technologies				
Dependent Variable: Circular Methods Use in Construction Steps				

Table 4.30. Coefficients for Hypothesis IV

	Unstandardized Coefficients		Standardized Coefficients	t	p
	B	Std. Error	Beta		
Digital Technologies	0.48	0.11	0.57	4.59	0.0001
Dependent Variable: Circular Methods Use in Construction Steps					

Linear Regression Analysis was conducted on the relationship between "Digital Technologies" and "Circular Methods Used in Construction Steps," which was found statistically meaningful in the Pearson Correlation Test. In the Linear Regression Analysis, the relationship between these two question groups was positive and statistically meaningful (p=0.0001). The R^2 value is 32.9%, while the Adjusted R^2 is 31.3%.

Table 4.31. Relationships Between All Question Groups

	Corporate Information			Awareness About Circularity			Circularity In Company Operations			Circular Methods Used in Construction Steps			Digital Technologies		
	N	**p**	**r**	**N**	**p**	**r**	**N**	**p**	**r**	**N**	**p**	**r**	**N**	**p**	**r**
Corporate Information				45	0.4090	-0.1260	45	**0.0030**	**-0.4330**	45	0.3500	-0.1430	45	0.1160	-0.2380
Awareness About Circularity	45	0.4090	-0.1260				45	**0.0230**	**0.3410**	45	**0.0330**	**0.3190**	45	0.1560	0.2150
Circularity In Company Operations	45	**0.0030**	**-0.4330**	44	**0.0230**	**0.3410**				44	**0.0001**	**0.5660**	44	**0.0250**	**0.3390**
Circular Methods Used in Construction Steps	45	0.3500	-0.1430	45	**0.0330**	**0.3190**	45	**0.0001**	**0.5660**				45	**0.0001**	**0.573**
Digital Technologies	45	0.1160	-0.2380	45	0.1560	0.2150	44	**0.0250**	**0.3390**	45	**0.0001**	**0.5730**			

A regression analysis was conducted on all the question groups to measure their relationships with each other. No statistically significant relationship was observed between “Corporate Information” and “Awareness About Circularity,” “Circular Methods Used in Construction Steps,” and “Digital Technologies” ($p>0.05$).

No statistically significant correlation was observed between “Awareness About Circularity” and “Digital Technologies ($p>0.05$). However, a statistically significant relationship was observed between “Awareness About Circularity” and “Circular Strategies in Company Operations” ($r=0.341$, $p=0.023$). Similarly, a statistically significant relationship was observed between “Awareness About Circularity” and “Circular Methods Used in Construction Steps” ($r=0.319$, $p=0.033$).

Statistically significant relationships were observed between “Circular Strategies in Company Operations” and “Awareness About Circularity” ($r=0.341$, $p=0.023$), “Circular Methods Used in Construction Steps” ($r=0.566$, $p=0.0001$), and “Digital Technologies” ($r=0.339$, $p=0.025$).

No statistically significant relationship was observed between “Circular Methods Used in Construction Steps” and “Corporate Information” ($r=-0.143$, $p=0.350$). However, statistically significant relationships were observed between “Circular Methods Used in Construction Steps” and “Awareness About Circularity” ($r=0.319$, $p=0.033$), “Circular Strategies in Company Operations” ($r=0.566$, $p=0.0001$), and “Digital Technologies ($r=0.573$, $p=0.0001$).

No statistically significant relationship was observed between “Digital Technologies” and “Corporate Information” and “Awareness About Circularity” ($p>0.05$). However, a statistically significant relationship was observed between “Digital Technologies” and Circular Strategies in Company Operations” ($r=0.339$, $p=0.025$). Similarly, a statistically significant relationship was observed between “Digital Technologies” and “Circular Methods Used in Construction Steps” ($r=0.573$, $p=0.0001$).

Table 4.32. Multivariate Linear Regression Analysis

R	R Square	Adjusted R Square	Std. Error of the Estimate	
0.703	0.494	0.456	0.63	
Change Statistics				
R Square Change	**F Change**	**df1**	**df2**	**p**
0.494	13.012	3	40	0.0001
Predictors: (Constant). Digital Technologies, Awareness About Circularity, Circular Strategies in Company Operations				
Dependent Variable: Circular Methods Use in Construction Steps				

Table 4.33. Coefficients for the Multivariate Linear Regression Analysis

	Unstandardized Coefficients		Standardized Coefficients	t	p
	B	Std. Error	Beta		
Awareness About Circularity	0.14	0.18	0.10	0.80	0.430
Circular Strategies Used in Company Operations	0.46	0.15	0.39	3.12	**0.003**
Digital Technologies	0.35	0.10	0.42	3.50	**0.001**
Dependent Variable: Circular Methods Used in Construction Steps					

A Multivariate Linear Regression analysis was conducted on the relationships that were found meaningful in the Linear Regression analyses: “Awareness About Circularity,” “Circular Strategies in Company Operations,” and “Digital Technologies.” The dependent variable is “Circular Methods Used in Construction Steps.” The R Square value is 49.4%, whereas the Adjusted R Square value is 45.6%, which has been proven to have statistically meaningful relationships. The variable “Awareness About Circularity” was not found statistically meaningful ($p>0.05$). However, the variables “Circular Strategies in Company Operations” ($p=0.003$) and “Digital Technologies” ($p=0.001$) were found statistically meaningful.

To further analyze the relationships between the question groups, a mediation analysis was conducted with “Circular Methods Used in Construction Steps,” “Awareness About Circularity,” “Circular Strategies in Company Operations,” and “Digital Technologies.”

Table 4.34. Variables for the Mediation Analysis

Dependent, Independent, and Proposed Mediator Variables:
DV = Circular Methods Used in Construction Steps
IV = Circular Strategies in Company Operations
MEDS = Awareness About Circularity, Digital Technologies

(DV=Dependent Variable, IV= Independent Variable, MEDS=Mediators)

Table 4.35. Model Breakdown

	R^2	**Adjusted R^2**	**F**	**df1**	**df2**	**p**
Model Summary for DV Model	0.494	0.456	13.01	3	41	**0.0001**

Table 4.36. Results of the Mediation Analysis

IV to Mediators (a paths)	**Coefficient**	**Standard Error**	**t**	**p**
Awareness About Circularity	0.269	0.115	2.35	**0.023**
Digital Technologies	0.482	0.207	2.33	**0.025**
Direct Effects of Mediators on DV (b paths)	**Coefficient**	**Standard Error**	**t**	**p**
Awareness About Circularity	0.144	0.181	0.80	0.430
Digital Technologies	0.351	0.100	3.50	**0.001**
Total Effect of IV on DV (c path)	**Coefficient**	**Standard Error**	**t**	**p**
Circular Strategies in Company Operations	0.672	0.151	4.45	**0.0001**
Direct Effect of IV on DV (c' path)	**Coefficient**	**Standard Error**	**t**	**p**
Circular Strategies in Company Operations	0.464	0.148	3.12	**0.003**

In the mediator relationship between “Circular Methods Used in Construction Steps” and “Circular Strategies in Company Operations,” the effects of “Awareness About Circularity” was found to be 26.9%, and for “Digital Technologies,” this value rises to 48.2%. Both effects are found statistically meaningful (p=0.023, p=0.025).

However, on the Direct Effect relationship between “Circular Methods Used in Construction Steps” and “Circular Strategies in Company Operations,” the effect of “Awareness About Circularity loses meaning by 14.4% and loses statistical meaning (p=0.430), while the effect of “Digital Technologies” is 35.1%, remaining statistically meaningful (p=0.001).

The total effect of “Circular Strategies in Company Operations” on “Circular Methods Used in Construction Steps” was found to be 67.2% as statistically meaningful (p=0.0001). The direct effect of “Circular Strategies in Company Operations” on “Circular Methods Used in Construction Steps” was found to be 46.4% as statistically meaningful (p=0.003).

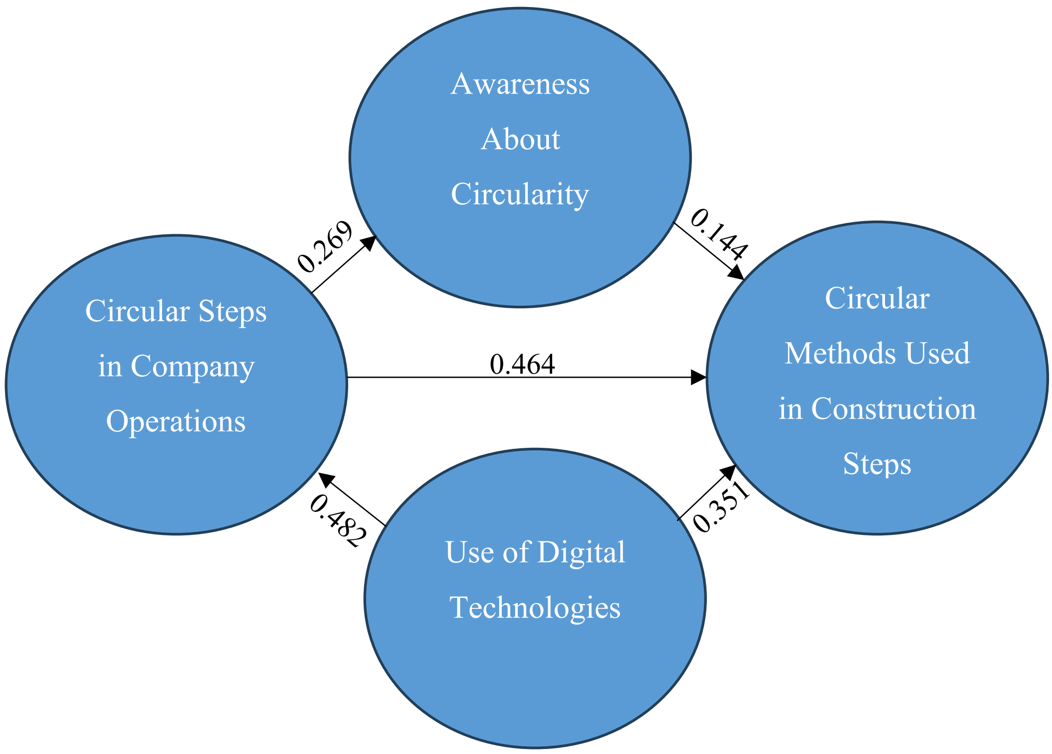


Figure 4.14. Relationships Between the Question Groups

CHAPTER 5

CONCLUSION

5.1 Introduction

This chapter initially summarizes the research with its materials, methods, and statistical tests that are conducted. Afterward, the results are explained and discussed in depth in the discussion part. Furthermore, the study's final remarks are presented. Finally, remarks for future studies are made.

5.2 Summary of the Research

The construction industry is one of the most significant sources of environmental degradation, energy use, and greenhouse gas emissions, and the conventional linear supply chains in the construction sector play an essential role in these harmful factors. Incorporating sustainable practices into the construction sector has become a topic of interest. The circular economy emerged as an enabler for sustainability in many sectors. The circular economy seeks to mitigate the consumption of natural resources, slow material use, and close waste material cycles. The construction sector holds massive potential for transitioning to a circular economy. In light of these concepts, the transition of construction supply chains from a linear state to a circular state is vital in tackling the harmful effects of the sector by efficient use of resources and minimization of environmental damage. The Turkish economy relies heavily on the construction sector. The impact of the industry on the overall economy is 30%. Therefore, transitioning Turkish construction supply chains to a circular economy would contribute heavily to sustainability on a national basis.

With the gap in the literature on achieving sustainability through transitioning to a circular economy in the construction supply chains in Turkey and a lack of guidelines for this transition in Türkiye, this research investigated the existing state of circularity in Turkish construction supply chains. Initially, a thorough literature review was conducted on sustainability, supply chains, construction supply chains, circularity, and how the concept of circularity can be integrated into construction supply chains. The literature review explores and explains circular strategies and phase-specific methods in depth. In light of the literature review, a framework for transitioning to a circular economy of construction supply chains was presented. Afterward, a questionnaire was prepared according to the proposed framework, with questions investigating the circular strategies and methods listed in the framework. This questionnaire comprises four parts: corporate information, awareness about circularity, circular strategies in company operations, and circular methods used in construction steps. Sixty-two construction companies with small-scale, mid-scale, and large-scale characteristics replied to the questionnaire. Among these replies, forty-five complete responses were identified, and the analysis was based on the forty-five complete responses to present the data more accurately. The questionnaire findings were presented in four parts through tables and bar charts. These results are discussed separately for each question in the four parts. Then, statistical tests, namely Pearson Correlation Test and Linear Regression Analysis, were applied to test four hypotheses that were created. Furthermore, a mediation analysis was made to see the relationships between question groups. The statistical tests are presented through tables and graphs and explained in depth. The findings of the analyses are described and discussed in depth in the following section.

5.3 Discussion

Authorities can use the proposed framework and questionnaire within the construction industry as a guideline for transitioning to a circular economy within supply chains. The framework provides a step-by-step guide to transforming a linear construction supply chain into a circular supply chain with strategies and phase-specific methods. It can also be used to create awareness and enhance the level of information the sector has on the concept of circularity in Türkiye. The statistical tests proved that the framework and the questionnaire prepared and conducted in light of the framework could investigate the existing state of circularity in Turkish construction supply chains and how certain factors relate. Furthermore, the reliability of the questionnaire was tested and proved by calculating the Cronbach Alpha values.

In the first step, the type of staff and their level of education were questioned to see whether these factors contribute to circular methods being used more intensively throughout construction supply chains. The variables were grouped under four headings: "Technical Staff," "Non-Technical Staff," "Educated Staff," and "Uneducated Staff." According to the questionnaire results, the majority of staff from the respondent companies are non-technical and uneducated due to the majority of staff being construction workers. Furthermore, the statistical tests show no meaningful relationship between the type of staff and circular methods used in the construction supply chain. Also, a statistically meaningful relationship was not found between the education level and the circular methods used. Therefore, whether the staff is educated or not and whether they possess technical knowledge do not contribute to the use of circular methods in construction steps.

In the second step, the relationship between the level of awareness of circularity and circular methods used in the construction supply chain was investigated. Furthermore, respondents' thoughts on the level of effects of the benefits of circularity were questioned. The results of this part show that most of the respondents are aware of the harmful effects of the construction sector on the environment. Furthermore, most respondents think the construction sector's efforts to eliminate these adverse effects are pretty low, and construction supply chains need to be more sustainable. Also, the results showed that the respondents possess mediocre knowledge of circularity and how it can be integrated into construction supply chains. These answers showed a statistically meaningful relationship with the amount of usage of circular methods used in construction supply chains. For the benefits of circularity on construction supply chains, according to the respondents, the most effective benefits are the environmental benefits, and the least effective benefits are the social benefits. Turkish construction specialists think that circularity has positive effects on the environment; however, they do not think that the positive impact of circularity on the social realm is that high. The statistical tests showed a positive correlation between these question groups, meaning that as the general awareness about circularity increases, the circular methods used in the construction supply chain steps increase. Furthermore, according to the regression analysis results, awareness about circularity affects the amount of circular strategies used in the company operations and circular methods used in the construction supply chain. As the level of awareness about circularity rises, companies tend to use more circular strategies in their operations and their use of circular methods in the steps of the construction supply chain increases. However, the level of awareness about circularity does not directly affect the relationship between circular strategies in the operations of companies and circular methods used in the steps of the construction supply chain; instead, it possesses a positive correlation between these factors separately. Furthermore, there is no relationship between the level of awareness about circularity and the use of digital technologies in the construction supply chain.

In the third part, the relationship between the circular strategies in the overall company operations and the circular methods used in the steps of the construction supply chain was investigated. Three strategies were identified in the literature review to be used in company operations, namely the “10 R Strategy” (see Chapter 2.5.1), “Circular Business Model Supply Chain Processes” (see Chapter 2.7), and the ReSOLVE Framework (see Chapter 2.7). The analysis showed that for the ReSOLVE Framework, the level of usage of the six strategies given in the framework is “Share>Virtualize>Optimize>Exchange>Regenerate>Loop.” This result shows that most companies show more effort to slow product loops, share products among users and reuse them, and elongate the lifetime of products through maintenance, repair, and design for durability, with respect to the other strategies within the ReSOLVE Framework. In the use of Circular Business Model Supply Chain Processes, it was seen from the analysis that the level of usage of circular strategies in the seven given processes is “Deliver>Use>Make>Plan>Source>Return>Recover.” However, the rates of usage for these processes are very similar. These results show that the most used circular strategies in the supply chain processes are used in the Deliver process, showing that companies show importance to delivering spare parts of products for maintenance and repair. In the 10 R Strategy, the ten given strategies are grouped under three aims: “smarter product use and production,” “extending the life of the product and its parts,” and “useful application of materials.” The results show that the strategy groups' use levels are “Extending the life of the product and its parts>Smarter production and use>Useful application of materials.” Furthermore, the most used strategy among the ten given strategies is “Repair.”

The results from these three strategies are coherent, showing that Turkish construction specialists put more effort into strategies related to maintenance and repair than strategies considering end-of-life practices since maintenance and repair provide benefits that accelerate the processes in a construction supply chain, being one of the significant aims of Turkish construction specialists. Furthermore, the statistical tests confirmed a positive relationship between the use of these three strategies in company operations and the circular methods used in the construction supply chain. This result means that as the use of the ReSOLVE Framework, the 10 R Strategy, and Circular Business Model Supply Chain Processes increases, more circular methods are used in the construction supply chain. Since these three strategies are used in corporate acts conducted throughout construction supply chains, Turkish construction specialists put more effort into using circular methods in each phase. Furthermore, these three strategies are correlated with the use of digital technologies in the construction supply chain.

The fourth part investigated the phase-specific methods and digital technologies to integrate circular methods into construction supply chains. The most used circular method in the design phase is design with customer feedback, whereas the least used method is design with recycled materials. This shows that while Turkish construction specialists show massive importance to the satisfaction of customers, they show little to no importance to designing with recycled materials. The circular method most used in the manufacturing and construction phase is the production of safe, resource-efficient materials, whereas the least used circular method used in this phase is the creation of material passports. Turkish construction specialists do not prefer to use relatively new technologies such as 3D printing of elements or material passports but rather prefer to use conventional circular methods like producing materials that are resource efficient, prefabrication of building assets, and green construction. In the operation and maintenance phase of the construction supply chain, the usage level of service life planning is more significant than tracking building performance and emissions. Furthermore, in the end-of-life phase, the most used circular method is on-site waste management, whereas the least used circular method in this phase is upcycling. On-site waste management is highly relied on in the Turkish construction sector, and it has multiple benefits, such as cost reductions, more accessible transportation, and the depreciation of pollution. Furthermore, the level of use of phase-specific circular methods is highest in the operation and maintenance phase and lowest in the manufacturing and construction phase. Turkish construction specialists use service-life planning and tracking of building emissions and performance commonly due to government implications for imposing energy identity cards to buildings over circular methods in the manufacturing and construction phase, resulting in high costs and elongated construction processes. Furthermore, when the use of circular methods was analyzed according to the project types of the respondent companies, it was found that companies that focus on infrastructure projects show massive importance to designing with life-cycle assessment. Since infrastructure projects require high investment, authorities aim to elongate the lifetime of the structure due to multiple reasons. Infrastructure projects hold colossal importance as a base for superstructure projects. Furthermore, due to massive amounts of investment, authorities want to elongate the structure's lifetime for as long as possible to increase the rate of return.

When the use of digital technologies was analyzed, it was found that BIM is the most commonly used digital technology throughout the Turkish construction supply chains. In contrast, Digital Twins is the least used digital technology. Turkish construction specialists' familiarity with digital technologies like BIM, GIS, and AI is greater than the more complex technologies like IoT, Big Data, Blockchain, and Digital Twins. The results show that Turkish construction specialists tend to use more conventional circular methods such as designing with customer feedback, producing safe materials, service life planning, and on-site waste management over more complex methods like life-cycle analysis, 3D printing, material passports, and reverse logistics due to their challenging nature and the lack of knowledge of Turkish construction specialists on specific complex methods.

According to the results of the statistical tests, while the type of staff and their education level do not affect the circular methods used in the steps of the construction supply chain, the awareness about circularity, circular strategies used in company operations, and the use of digital technologies positively correlate with the use of circular methods in the construction supply chain steps. Furthermore, according to the multivariate regression analysis, the circular methods used in construction steps are mainly correlated with the use of digital technologies and circular strategies in company operations. This result means that as Turkish construction specialists integrate more digital technologies into their supply chains, more circular methods are used in the steps of the construction supply chain. Furthermore, as companies integrate more circular strategies in their operations, more circular methods are used in the construction phases. When the relationship between the circular strategies in company operations and circular methods used in the steps of the construction supply chain is tested, it was seen that the use of digital technologies significantly affects this relationship. Since digital technologies have multiple benefits by means of circularity within construction supply chains, such as reductions in time and costs, as more digital technologies are integrated into construction supply chains, more phase-specific circular methods are used. Therefore, digital technologies assist Turkish construction specialists in transitioning to circularity in construction supply chains.

5.4 Final Remarks

Transitioning to a circular economy in the Turkish construction sector is vital to achieve sustainability. While Turkish construction supply chains hold massive potential for this transition, Turkish construction specialists possess mediocre knowledge of circularity. Furthermore, they think circularity highly affects environmental, economic, and social factors, bringing many benefits to each factor. Three strategies are derived from the literature review to see their usage level in Turkish construction companies' operations. The study found that the ReSOLVE Strategy, 10 R Strategy, and Circular Business Model Supply Chain Processes are mediocrely used in Turkish construction supply chains with similar use rates. Furthermore, phase-specific circular methods are derived from the literature review to see their usage level in the respective phases of Turkish construction supply chains. It was found that while circular methods are primarily used in the operation and maintenance phase, the circular methods that are tested are mediocrely used in the design, manufacturing and construction, operation and maintenance, and end-of-life phases of a project. The use of seven digital technologies is also questioned among Turkish construction specialists, and it was seen that while software like Building Information Modeling and Geographical Information Systems are used in general, the rate of use of relatively new and more complex technologies such as IoT and Digital Twins is low. Integrating more circular methods and digital technologies in each phase of a construction supply chain is vital for transitioning to a circular economy. The statistical tests show that while the types of staff and their education level do not affect the level of use of circular methods in the phases of construction supply chains, the awareness about circularity, circular strategies in company operations, and the use of digital technologies have positive correlations on the level of use of circular methods. Furthermore, it was found that the use of circular strategies in company operations is directly related to circular methods used in the phases of a construction supply chain, and digital technologies affect this relationship.

5.5 Future Studies

This study presents an overview of the existing state of circularity in Turkish construction supply chains. The proposed framework for transitioning to a circular economy and the questionnaire can be utilized in future studies with a more crowded population to collect and interpret more data. On the other hand, the framework and questionnaire can be presented to a smaller population in city-specific research. Furthermore, the method and material of this research can be adapted to the countries to see the existing state of circularity in the construction supply chains on a country-specific scale. The results of this study on the Turkish case can be compared with those of other countries.

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APPENDICES

A. QUESTIONNAIRE

Corporate Information

CI.1. Please indicate the type and number of staff working in your company.

CI Q1.1 Administrative Staff	
CI Q1.2 Technical Staff	
CI Q1.3 Non-Technical Staff	
CI Q1.4 Other	

CI.2. Please indicate the education level of the staff working in your company and their numbers.

CI Q2.1 Undergraduate	
CI Q2.2 Graduate	
CI Q2.3 PhD	
CI Q2.4 Other	

Awareness About Circularity

AAC Q3. How much do you think the construction industry contributes negatively to environmental factors such as climate change, carbon dioxide emissions, and material waste today?

a) 1
b) 2
c) 3
d) 4
e) 5

AAC Q4. How much effort do you think the construction industry in our country is making to eliminate the problems described above?

a) 1
b) 2
c) 3
d) 4
e) 5

AAC Q5. How much necessary do you think it is to make construction supply chains more sustainable?

a) 1
b) 2
c) 3
d) 4
e) 5

AAC Q6. How much do you know about the concept of circularity and how this concept can be integrated to the construction industry?

a) 1
b) 2
c) 3
d) 4
e) 5

AAC Q7. Mark the level of effects of a circular construction supply chain on the factors listed below.

Factors		Level of Effect				
		1	2	3	4	5
Environmental Factors	**AAC Q7.1.** Decreasing the need for primary production through secondary production	□	□	□	□	□
	AAC Q7.2. Using fewer resources and increasing efficiency	□	□	□	□	□
	AAC Q7.3. Reducing greenhouse gas emissions	□	□	□	□	□
	AAC Q7.4. Material savings and recycling	□	□	□	□	□
	AAC Q7.5. Decreasing of waste	□	□	□	□	□
	AAC Q7.6. Protection of natural resources	□	□	□	□	□
Economic Factors	**AAC Q7.7.** Decreasing of costs	□	□	□	□	□
	AAC Q7.8. Creation of value	□	□	□	□	□
	AAC Q7.9. Enhanced resource security	□	□	□	□	□
	AAC Q7.10. Increasing profits	□	□	□	□	□
	AAC Q7.11. Balancing price volatility	□	□	□	□	□
	AAC Q7.12. Reducing the dependency on imports	□	□	□	□	□
Social Factors	**AAC Q7.13.** Advanced social rights and human rights	□	□	□	□	□
	AAC Q7.14. Creation of new job opportunities	□	□	□	□	□
	AAC Q7.15. Social equity	□	□	□	□	□
	AAC Q7.16. Sharing economy	□	□	□	□	□
	AAC Q7.17. Participation and democracy	□	□	□	□	□
	AAC Q7.18. Health and safety of workers	□	□	□	□	□
	AAC Q7.19. Increased benefits to customers	□	□	□	□	□
	AAC Q7.20. Engaged employees	□	□	□	□	□
	AAC Q7.21. Eco-development	□	□	□	□	□

Circular Strategies in Company Operations

CSCO Q8. Mark your level of application of the strategies listed below in the processes of your existing supply chain.

Supply Chain Process	Strategy	Level of Application				
		1	2	3	4	5
CSCO Q8.1. Plan	Planning the supply chain requirements and resources taking into consideration the Use and Recover phases in a supply chain.	□	□	□	□	□
CSCO Q8.2. Source	Sourcing materials that can lead to return, disassembly, and recovery.	□	□	□	□	□
CSCO Q8.3. Make	Resource efficient production with additional focus on waste management.	□	□	□	□	□
CSCO Q8.4. Deliver	Delivering of maintenance and repair-friendly products to extend the product's lifetime.	□	□	□	□	□
CSCO Q8.5. Use	The maintenance and repairing of the product to enhance its lifetime.	□	□	□	□	□
CSCO Q8.6. Return	The collection and delivery of products to a facility after the end-of-life of the product to enable waste process and/or recovery.	□	□	□	□	□
CSCO Q8.7. Recover	The reuse, remanufacturing, refurbishing, upcycling, downcycling, and recycling of products at the end-of-life phase of the product.	□	□	□	□	□

CSCO Q9. Mark your level of application of the methods listed below in the running of your existing supply chain.

Method	Level of Application				
	1	2	3	4	5
CSCO Q9.1. Shift to renewable energy and materials; reclaim, retain, and regenerate ecosystems' health; and return to the biosphere the recovered biological resources.	◻	◻	◻	◻	◻
CSCO Q9.2. Elongating the lifetime of buildings through maintenance, repair, and design for durability.	◻	◻	◻	◻	◻
CSCO Q9.3. Increasing the performance and efficiency of buildings, removing waste in production and supply chain, leveraging, and using of digital technologies.	◻	◻	◻	◻	◻
CSCO Q9.4. Remanufacturing products or components used in the making of a building, recycling materials, and extracting biochemicals from organic waste.	◻	◻	◻	◻	◻
CSCO Q9.5. Virtualizing the process of construction via digital technologies.	◻	◻	◻	◻	◻
CSCO Q9.6. Replacing old materials with advanced non-renewable materials, application of new technologies and choosing new products and/or services.	◻	◻	◻	◻	◻

CSCO Q10. Mark your level of usage of the circular steps listed below in your construction supply chain.

Steps			Level of Usage				
Aim	**Strategy**	**Explanation**	**1**	**2**	**3**	**4**	**5**
Smarter product use and production	**CSCO Q10.1.** Refuse	Make product unnecessary through abandoning its function or by offering the same function with a different product	☐	☐	☐	☐	☐
	CSCO Q10.2. Rethink	Make product use more intensive	☐	☐	☐	☐	☐
	CSCO Q10.3. Reduce	Using fewer natural resources and materials, increasing the efficiency in the production and use of the product.	☐	☐	☐	☐	☐
Extending the life of the product and its parts	**CSCO Q10.4.** Reuse	Reusing a product which is still in good state and can present its original function by another customer.	☐	☐	☐	☐	☐
	CSCO Q10.5. Repair	Repair and maintenance of defective product so it can be use with its original function.	☐	☐	☐	☐	☐
	CSCO Q10.6. Refurbish	Restoring an old product and bring it up to date.	☐	☐	☐	☐	☐
	CSCO Q10.7. Remanufacture	Using the parts of a discarded product in a new product with the same function.	☐	☐	☐	☐	☐
	CSCO Q10.8. Repurpose	Use discarded product or its parts in a new product with a different function.	☐	☐	☐	☐	☐
Useful application of materials	**CSCO Q10.9.** Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality.	☐	☐	☐	☐	☐
	CSCO Q10.10. Recover	Energy recovery.	☐	☐	☐	☐	☐

Circular Methods Used in Construction Steps

CMUCS Q11. Mark your level of usage of the methods listed below to achieve a circular supply chain in the architectural and engineering design phase of a project.

Method	Level of Usage				
	1	2	3	4	5
CMUCS Q11.1. Design with LCA	□	□	□	□	□
CMUCS Q11.2. Design with reused materials	□	□	□	□	□
CMUCS Q11.3. Design with recycled materials	□	□	□	□	□
CMUCS Q11.4. Design for deconstruction	□	□	□	□	□
CMUCS Q11.5. Design for adaptability	□	□	□	□	□
CMUCS Q11.6. Design with customer feedback	□	□	□	□	□

CMUCS Q12. Mark your level of usage of the methods listed below to achieve a circular supply chain in the manufacturing and construction phase of a project.

Method	Level of Usage				
	1	2	3	4	5
CMUCS Q12.1. Production of safe resource efficient materials	□	□	□	□	□
CMUCS Q12.2. Use of renewable and biobased materials	□	□	□	□	□
CMUCS Q12.3. Creation of material passports	□	□	□	□	□
CMUCS Q12.4. Prefabrication of elements	□	□	□	□	□
CMUCS Q12.5. Use of green construction methods	□	□	□	□	□
CMUCS Q12.6. 3D printing of elements	□	□	□	□	□

CMUCS Q13. Mark your level of usage of the methods listed below to achieve a circular supply chain in the operation and maintenance phase of a project.

Method	Level of Usage				
	1	2	3	4	5
CMUCS Q13.1. Service life planning	□	□	□	□	□
CMUCS Q13.2. Tracking of building performance and emissions	□	□	□	□	□

CMUCS Q14. Mark your level of usage of the methods listed below to achieve a circular supply chain in the end-of-life phase of a project.

Method	Level of Usage				
	1	2	3	4	5
CMUCS Q14.1. Diversion of wastes	□	□	□	□	□
CMUCS Q14.2. Identification of reusable and recyclable components	□	□	□	□	□
CMUCS Q14.3. On-site waste management	□	□	□	□	□
CMUCS Q14.4. Upcycling	□	□	□	□	□
CMUCS Q14.5. Downcycling	□	□	□	□	□
CMUCS Q14.6. Reverse logistics	□	□	□	□	□

CMUCS Q15. Mark your level of usage of the digital technologies listed below to create a circular construction supply chain.

Digital Technologies	Level of Usage				
	1	2	3	4	5
CMUCS Q15.1. BIM (Building Information Modelling)	□	□	□	□	□
CMUCS Q15.2. IoT (Internet of Things)	□	□	□	□	□
CMUCS Q15.3. Artificial Intelligence (AI)	□	□	□	□	□
CMUCS Q15.4. Big Data	□	□	□	□	□
CMUCS Q15.5. Blockchain	□	□	□	□	□
CMUCS Q15.6. GIS (Geographic Information System)	□	□	□	□	□
CMUCS Q15.7. Digital Twins	□	□	□	□	□

B. ETHICAL BOARD APPROVAL

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06 MAYIS 2024

Konu: Değerlendirme Sonucu

Gönderen: ODTÜ İnsan Araştırmaları Etik Kurulu (İAEK)

İlgi: İnsan Araştırmaları Etik Kurulu Başvurusu

Sayın Ali Murat Tanyer

Danışmanlığını yürüttüğünüz Elif Naz Yılmaz'ın ***"Türk İnşaat Tedarik Zincirinin Döngüsel Ekonomi Prensipleri ile Değerlendirilmesi."*** başlıklı araştırmanız İnsan Araştırmaları Etik Kurulu tarafından uygun görülerek **0319-ODTUİAEK-2024** protokol numarası ile onaylanmıştır

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