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SCHOOL OF ARCHITECTURE URBAN PLANNING CONSTRUCTION ENGINEERING
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UPCYCLING TEXTILE WASTE FROM THE FASHION INDUSTRY AS A SUSTAINABLE BUILDING MATERIAL FOR ARCHITECTURAL DESIGN

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1 Table of Contents

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Carbon footprint - The total amount of greenhouse gases (GHG) emitted by an organization or product during the duration of its operation or manufacturing.

Downcycling - Downcycling is a term that refers to a recycled product that is not as structurally sound like a virgin product.

Fabric scraps - A small leftover piece of fabric that is unusable for another project by itself.

Greenhouse gases (GHG) - A class of gases listed by the IPCC as being responsible for increasing global warming, comprising carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, and perfluorocarbons.

Landfill - A landfill is a location where waste items are disposed of.

Post-consumer waste - Waste type in textile industry refers to all apparel dumped by consumers because it has become stale or unfashionable.

Pre-consumer waste (post-industrial waste) - Waste type in textile industry refers to all-fiber, yarn, and fabric waste generated during garment manufacturing.

Screen - A screen is an upright barrier, whether permanent or mobile, to divide a space, protect from draughts, heat, light, or conceal or protect privacy.

Sustainability - Sustainability encompasses economic, social, and environmental factors. Organic materials, recycled synthetic fibers, and/or renewable resources; resource reduction, reuse and recycling (raw materials, energy, water) required at all stages of the product life cycle, from production to consumption; reduction of chemical use and disposal as well as air pollution and waste generation in the production process (Jacometti, 2019).

Textile recycling - Textile recycling is a method of converting used garments and other textiles into new textile or non-textile products.

Textile reuse - Textile reuse is a method of recovering used garments and other textiles for reuse or material recovery.

Textile waste - Textile waste is a substance that has been determined by the owner to be useless for its initial purpose. Textile waste may be divided into fashion and textile industry waste, which is generated during the manufacture of fiber, textile, and apparel, and consumer waste, which is generated during consumer usage and disposal.

Upcycling – The term is defined as the process of recycling textile waste into materials for new goods with a higher economic and environmental value.

ABSTRACT

English

As one of the most significant areas of the Italian economy, the capacity of the Italian textile industry contributes to the country's prosperity. However, fashion is one of the most prevalent consumer waste streams, with 466 tonnes discarded in Italy every year due to a growing interest and fast change in the textile industry. On the other hand, textile materials are wasted daily worldwide, accounting for around 1.5 percent of total waste generation. The latest developments show that composite materials based on textile waste such as low-requirement building materials have significant expansion in the market.

This study investigates a circular textiles system for innovative sustainable materials and the capability of textile waste fibers to produce higher-quality products. It aims to find novel ways to use textile leftovers as building materials contributing to greener interior design.

In this research study, the textile wastes obtained from the Italian company Ratti SpA (i.e., silk, cotton, and viscose) were investigated to be utilized as fibers (matrix) to create an upcycled interior architectural product by combining with a bio-based binder. In the experiment phase, a series of physical experiments were completed, several samples, consisting of different fiber size variations of silk-based, cotton-based, and viscose-based composites, were produced and tested to measure their sound absorbent performance. Test *results showed that the viscose-based composite with small-sized fibers exhibited the best acoustic performance having a higher sound-absorbent capacity for the low frequencies.*

On the other hand, the lightest samples having the lowest density belong to the silk-based composites, while cotton-based composites have a higher volume with higher weight. The design project phase was conducted to analyze the potential use of textile-waste-based composites for interior architectural implementations. As a result of the studies, new prototypes were suggested to be created in the brick and panel forms to facilitate various configurations used as screens, sound-absorbent wall covering, and furniture in the office interior.

Keywords: Textile waste, Circular model, Recycling and upcycling, Textile-based architectural design

ABSTRACT

Italian

Essendo una delle aree più significative dell'economia italiana, la portata dell'industria tessile italiana contribuisce alla prosperità del Paese. Tuttavia, la moda crea uno dei principali flussi di rifiuti di consumo, con 466 tonnellate scartate in Italia ogni anno a causa di un crescente interesse e di un rapido cambiamento nell'industria tessile. D'altra parte, i materiali tessili vengono sprecati ogni giorno in tutto il mondo, rappresentando circa l'1,5% della produzione totale di rifiuti. Gli ultimi sviluppi mostrano che i materiali compositi basati su rifiuti tessili, come i materiali da costruzione a basso fabbisogno, hanno una significativa espansione nel mercato.

Questo studio indaga su un sistema tessile circolare per materiali sostenibili innovativi e la capacità delle fibre di scarto tessili di produrre prodotti di qualità superiore. Mira a trovare nuovi modi per utilizzare gli avanzi tessili come materiali da costruzione che contribuiscono a un design degli interni più ecologico.

In questa ricerca, i rifiuti tessili ottenuti dall'azienda italiana Ratti SpA (seta, cotone e viscosa) sono stati studiati per essere utilizzati come fibre (matrice) per creare un prodotto architettonico per interni riciclato combinandolo con un legante a base biologica. Nella fase sperimentale, sono stati completati una serie di esperimenti fisici, sono stati prodotti e testati diversi campioni, *costituiti da diverse variazioni di dimensione delle fibre di compositi a base di seta, cotone e viscosa, per misurarne le prestazioni fonoassorbenti. I risultati dei test hanno mostrato che il composito a base di viscosa con fibre di piccole dimensioni ha mostrato le migliori prestazioni acustiche avendo una maggiore capacità fonoassorbente per le basse frequenze.*

Appartengono invece ai compositi a base di seta i campioni più leggeri e con la densità più bassa, mentre i compositi a base di cotone hanno un volume maggiore con un peso maggiore. La fase del progetto di design è stata condotta per analizzare il potenziale utilizzo di compositi a base di rifiuti tessili per implementazioni architettoniche di interni. Come risultato degli studi, è stato suggerito di creare nuovi prototipi nelle forme del mattone e del pannello per facilitare le varie configurazioni utilizzate come schermi, rivestimento murale fonoassorbente e mobili all'interno dell'ufficio.

Parole chiave: Rifiuti tessili, Modello circolare, Riciclaggio e upcycling, Prodotti per interni a base tessile

1 INTRODUCTION

The textile industry ranks third in Italy's industrial sector in terms of economic significance, which has grown primarily in the north, particularly in the Upper Milan area, surrounding Como and Bergamo. In Italy, the fashion sector is regarded as a model of excellence, and the industry's profits are impressive. On the other hand, the textile system has consumed millions of gallons of water and chemicals, including insecticides for growing raw materials like cotton to manufacture, spinning them into fibers, weaving fabrics, and dyeing. When worn clothes are no longer needed, less than half is collected for reuse or recycling, barely 1% is converted into new apparel because recycling clothes into virgin fibers has been just emerging in the EU (Bourguignon, 2018).

The fabric waste from the fashion industry is extremely high. The fashion cycle renders styles outdated before the end of life of textile items, resulting in wastes and overconsumption that harm the environment. Most of these wastes are burned or deposited. Incorporating textile waste into a new manufacturing process might help accomplish sustainable waste management while increasing the value of new goods (Rubino, 2021). In other words, waste management can be addressed by recycling and repurposing fabric scraps in the fashion industry.

Pre-consumer waste, also known as post-industrial waste, refers to all-fiber, yarn, and fabric waste generated during garment manufacturing. In contrast, post-consumer solid waste refers to all apparel dumped by consumers because it has become stale or unfashionable. Recycling pre-and post-consumer waste can significantly assist in mitigating the environmental effect of the textile industry by reducing the requirement for landfill space (Rubino et al., 2018). It is predicted that at least 75% of pre-consumer waste must be recycled in order to significantly reduce the carbon footprint of a textile product (Muthu et al., 2012).

At the request of the European Parliament, the EU enacted a circular economy package in 2018 that will, for the first time, ensure that textiles are collected separately in all Member States by 2025 at the earliest. For years, the European Parliament has campaigned to promote using environmentally friendly and sustainable raw materials and recycling clothes (Sajn, 2019).

If supported by international policy continues, the circular economy can be a catalyst of innovation and an opportunity for a wide range of industries, including construction. The data reported in the document titled "Towards a circular economy model for Italy"[1] published by the Italian Ministry of the Environment emphasize the building industry's strategic relevance in creating an economy in which resource sustainability and waste management become critical components of a new development model (dell'Ambiente, n.d.). In this regard, Italy has implemented Minimum Environmental Criteria (CAM), a set of public policy instruments to encourage the use of recycled-content goods and low-impact materials throughout their life cycle (Tedesco & Montacchini, 2020).

[1] https://ec.europa.eu/growth/sectors/fashion/textiles-and-clothing-industries_it

Furthermore, the building sector has developed substantially over the previous few decades, and as a result, its negative environmental impacts have increased. Traditional structures require enormous amounts of energy and raw materials during their lifespan, construction, and destruction phases. Today, the construction sector accounts for a sizable portion of Europe's energy consumption and carbon emissions. Statistically, the building sector is in charge of 40% of energy consumption and 36% of carbon emissions in the European Union (Huang et al., 2018).

Consumption of raw materials, including construction and building sectors, at an unsustainable rate would undoubtedly result in resource shortages for future generations. Hence, it is vital to create long-term plans for energy conservation. Environmental impacts connected with the construction sector might be mitigated to reduce carbon footprint worldwide. Examining materials made from secondary raw resources can present an opportunity (Rubino et al., 2018) to lower the environmental impacts and find ecological solutions in the construction sector. Therefore, textile leftovers from the fashion industry can be utilized in different sectors, especially construction.

Consequently, the textile and construction industry generates excessive carbon dioxide. Finding sustainable solutions is obligatory for the future. This study explores a new methodology for upcycling the textile waste from the fashion industry as a building material to contribute to the goals of the European Commission's objectives (2020) of increasing sustainable and circular material choices to reduce the carbon footprint caused by 40% of it by the construction industry. Besides, the negative impacts of the fashion sector accounting for 10% of the global greenhouse gas emissions with four million tonnes should be a concern. This study's primary objective is to prove that to mitigate the environmental audits of the products manufactured for the construction industry by replacing the newly produced construction materials with the textile leftovers used.

1.1 Motivations of the Research

According to a global study of industrial sectors, the textile industry is one of the most destructive to the environment, both in supply chain activities and pre-and post-consumer waste. It emits millions of tons of greenhouse gases into the atmosphere each year and consumes millions of liters of water in the processing of millions of tons of industrial chemicals, resulting in a substantial environmental impact.

Apart from the harmful effects of textile processing prior to distribution, less than 1% of the materials used to produce clothes are recycled in a closed-loop system, and less than 2% of the materials are reused in other industrial sectors. From the sustainability point of view, this thesis focuses on the reuse of textile waste in the building sector regarding the difficulties associated with developing a sustainable waste management system in the textile industry. Demanding new design methods can shift waste attitude by investigating alternative design solutions through a circular economy perspective. Offering interdisciplinary design solutions is feasible to increase the value of a product without consuming more natural resources and raw materials.

1.2 Research Questions and Objectives

Most textile waste, particularly fibers from industrial applications, is disposed of in landfills. With this in mind, and intending to increase the amount of potentially recyclable and reusable textile waste, this research study proposed to address the issue by combining creative uses for waste textile fiber with a natural and hand-made binder to simplify the process for any scale of production, thereby increasing the amount of recycled textile waste. The question is how textile waste and a bio-based binder can be combined to create a new type of application and how architecture and textile waste can collaborate to answer that question.

This study investigated transforming textile waste into fiber-based material compositions to produce a low-requirement interior building industry. Concerning this, a series of physical experiments were implemented; three different textile fibers, including 100% silk, 100% cotton and, 100% viscose, are mixed with two different bio-based binders, including starch-based and casein-based glue. Produced material samples are evaluated to determine their suitability as sound absorption materials and capability of scaling up.

The textile scraps were supplied by the private Italian company Ratti SpA[2] (Milan, Italy), a large-sized business that provides textile scraps. The samples were produced in the Material Balance Research Group[3] laboratory in Politecnico di Milano's ABC (Architecture Built Environment and Construction Engineering) department. Sound absorption performances of the samples

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[2] https://www.ratti.it/

[3] https://www.materialbalance.polimi.it/

were tested in the PSVL (Polimi Sound and Vibration Laboratory) with the collaboration of Andrea Giglio in Politecnico di Milano.

Primary objectives were identified to explore sustainable and novel material systems:

1. Comprehending the textile industry and current textile waste management in Europe and Italy,
2. Analyzing the environmental impacts of textile leftovers, the drawbacks of the linear textiles system, and the need for transition to a circular textiles system,
3. Exploring the ways for reusing textile waste as a resource by transforming it into new materials or products perceived to be of more superior quality (upcycling) to produce precisely a textile-waste-based circular building material,
4. Evaluating the best-produced material samples through their application as a sound absorption material and its suitability to scale up for office interior use.

The following chapters will discuss the research context, state of the art in corresponding application scenarios, the methodology used in the study, and some innovative implementations of architectural applications using textile waste that were conducted to address research questions and achieve the associated objectives.

2 TEXTILE INDUSTRY

Textiles are essential in our civilization, involved with the design, manufacturing, distribution of yarns and apparel, supplying us with clothing, shoes, rugs, curtains, furniture, and more. As one of the world's foremost and competitive industries, the garments employ millions of people (technicians, engineers, artists) and contribute significantly to European manufacturing. On the other hand, the production and consumption of textiles pollute the environment by utilizing water, land, and chemicals and producing greenhouse gases. This briefing addresses how circular business models and legislation may help us towards a circular textiles sector (Zhongming et al., 2019).

The manufacturing and consumption of textiles are highly globalized, involving millions of producers and billions of customers worldwide. As the population grows and the economy develops, the overall demand for textile products has expanded consistently (Sandin & Peters, 2018). In order to reduce environmental and climate consequences while retaining the economic and social advantages of the textile industry, a systematic shift towards circularity is required. Circular business models and effective rules addressing materials and design, production and distribution, usage and reuse, collection, and recycling will be necessary to achieve the circular textiles system. This future vision encompasses green sourcing, eco-design, extended producer responsibility, environmental labeling, and standards (Zhongming et al., 2019).

2.1 Textile Industry in Europe

Globalization has had a significant impact on textile production and consumption. The textiles sector has a €166 billion revenue and 176.400 businesses (mainly small-medium entrepreneurs) and employs approximately 1.7 million people in Europe[4].

As illustrated in Figure 1, for 2018, 85 percent of all textile imports into the EU originate from only ten countries, with China accounting for 37%, Turkey accounting for 11%, Bangladesh accounting for 10%, and India accounting for 9%. Exports are more fragmented than imports, with the top ten destination nations accounting for 55% of total volume exports, with 10% going to China, 9% to Turkey, 8% to the United States, and 5% to Pakistan.

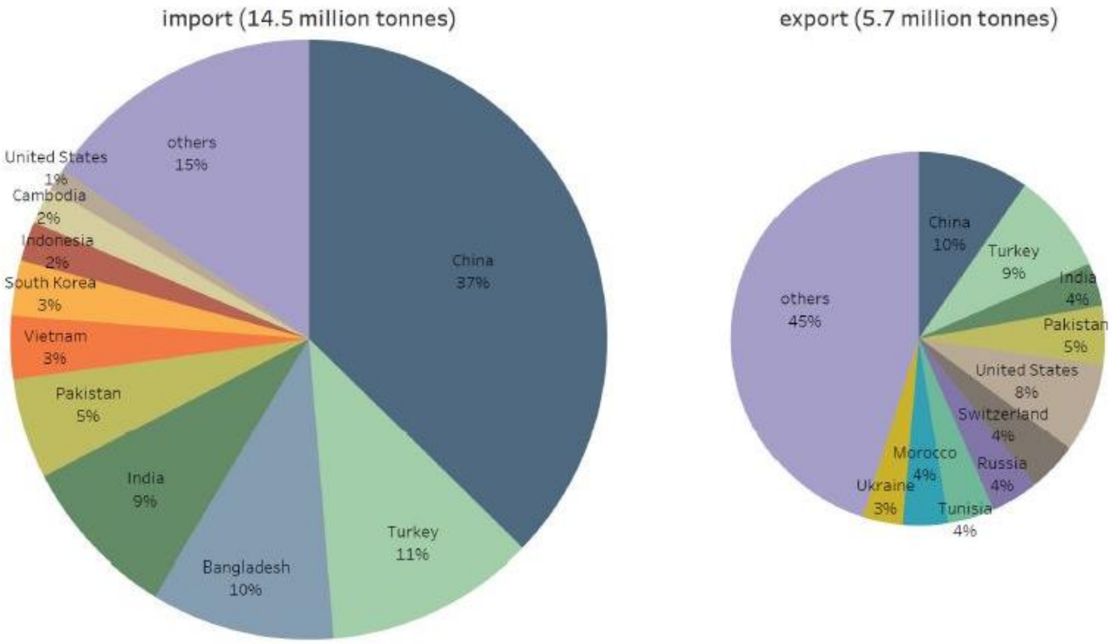

Figure 1. *By country, 2018 percentage of EU imports and exports*
Source: The Harmonized Commodity Description and Coding System, Chapters 50–67 (2017)

[4] https://ec.europa.eu/growth/sectors/fashion/textiles-and-clothing-industries_it

In 2017, as seen in Figure 2, although households in European countries produced 7.4 kg of textiles per person, the consumption amount in Europe was over 26 kilos of textiles per person (Vercalsteren et al., 2019). This estimate is subject to inconsistency, as multiple studies worldwide report estimations ranging from 9 to 27 kg per person, depending on the data source and scope of the material (Watson et al., 2018; Šajn, 2019). The European Commission's Joint Research Centre (JRC) previously estimated the average annual consumption of clothing and domestic textiles in the EU at 19.1 kg per person (Beton et al., 2014).

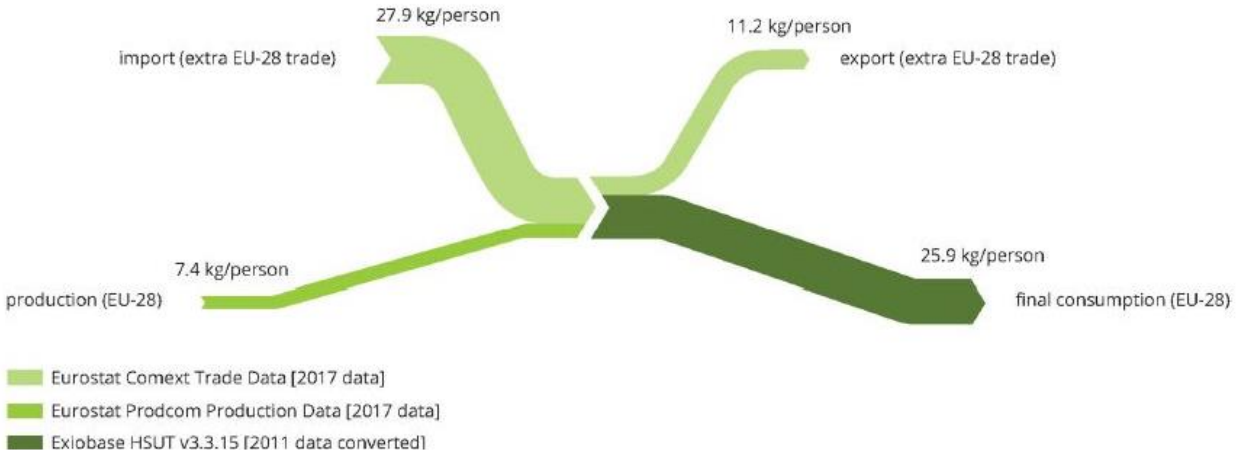

***Figure 2**. Summary of the import, export, production, and consumption of textile in Europe for 2017 (Source: Vercalsteren et al., 2019).*

The amount of garments purchased per person in the European Union has proliferated by 40% in just a few decades due to lower pricing and faster fashion delivery to customers. Clothing has been responsible for between 2% and 10% of the environmental effect of EU consumption in recent years (Sajn, 2019). Moreover, clothing, footwear, and home textiles are the fourth- or fourth-worst-ranked pressure sectors for primary raw material and water usage when looking at supply chain pressures from an EU consumer viewpoint (after food, housing, and transport). It ranks second in land usage and fifth in greenhouse gas emissions (Zhongming et al., 2019).

One of the terrible consequences of such high levels of manufacturing and, by extension, consumption is the amount of textile waste created when products are discarded. An estimated 5.8 million tonnes of textiles, which means an average of 11 kg per person, are discarded by EU citizens each year. According to Eurostat (2016) data, the textile waste collected separately in 2016 was estimated at 2 million tonnes. Estimates of collection rates (share of the quantity placed on the market) vary significantly between countries, ranging from 0.2 to 12.5 kilograms per person; on average, about one-third of the volume placed on the market is collected separately (European Commission, 2020), implying that an even greater volume of textile waste ends up in residual waste (Zhongming et al., 2019).

According to Eurostat statistics shown in Figures 3, Italy was fourth among the European Countries (EU) for the amount of annual textile waste production per person. Moreover, it also shows that Italy was the largest textile polluter in the EU when the population was taken into consideration, and the amount of total produced textile waste was approximately 466 thousand tonnes in 2016. Italy was followed by Germany, France, and the United Kingdom, which dumped more than 200,000 tonnes of textiles in the same year. When subdivided by population, this figure fluctuated between little more than two kilos and over 15 kilograms of textile waste per year (Statista, 2021).

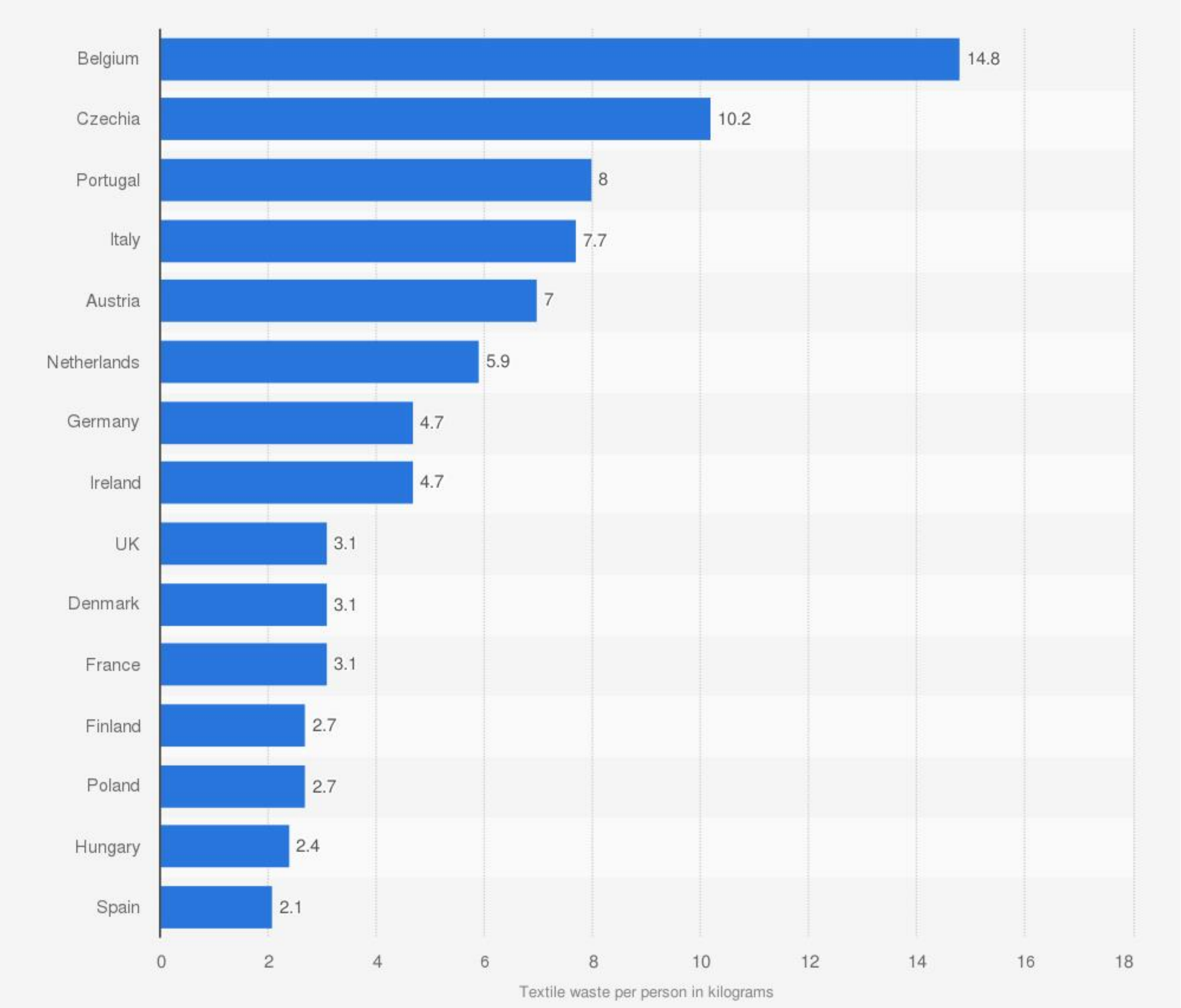

Figure 3*. The EU's annual textile waste production, subdivided by country, in 2016 (kilograms). (Source:https://www.statista.com/statistics/1090566/textile-waste-generated-in-the-european-union-per-person/).*

Another data for 2016 published by Eurostat shows that while households from Italy produced an annual 7.7 kg of textile waste per person, the annual recycled textile per person was only 0.8 kg (Figure 4). The statistic in Figure 4 demonstrates that even though Italy had the largest demand for textile products and consumed more than the average value of European countries, recycling textile products to meet demand was not prioritized, and continuous textile imports were undertaken.

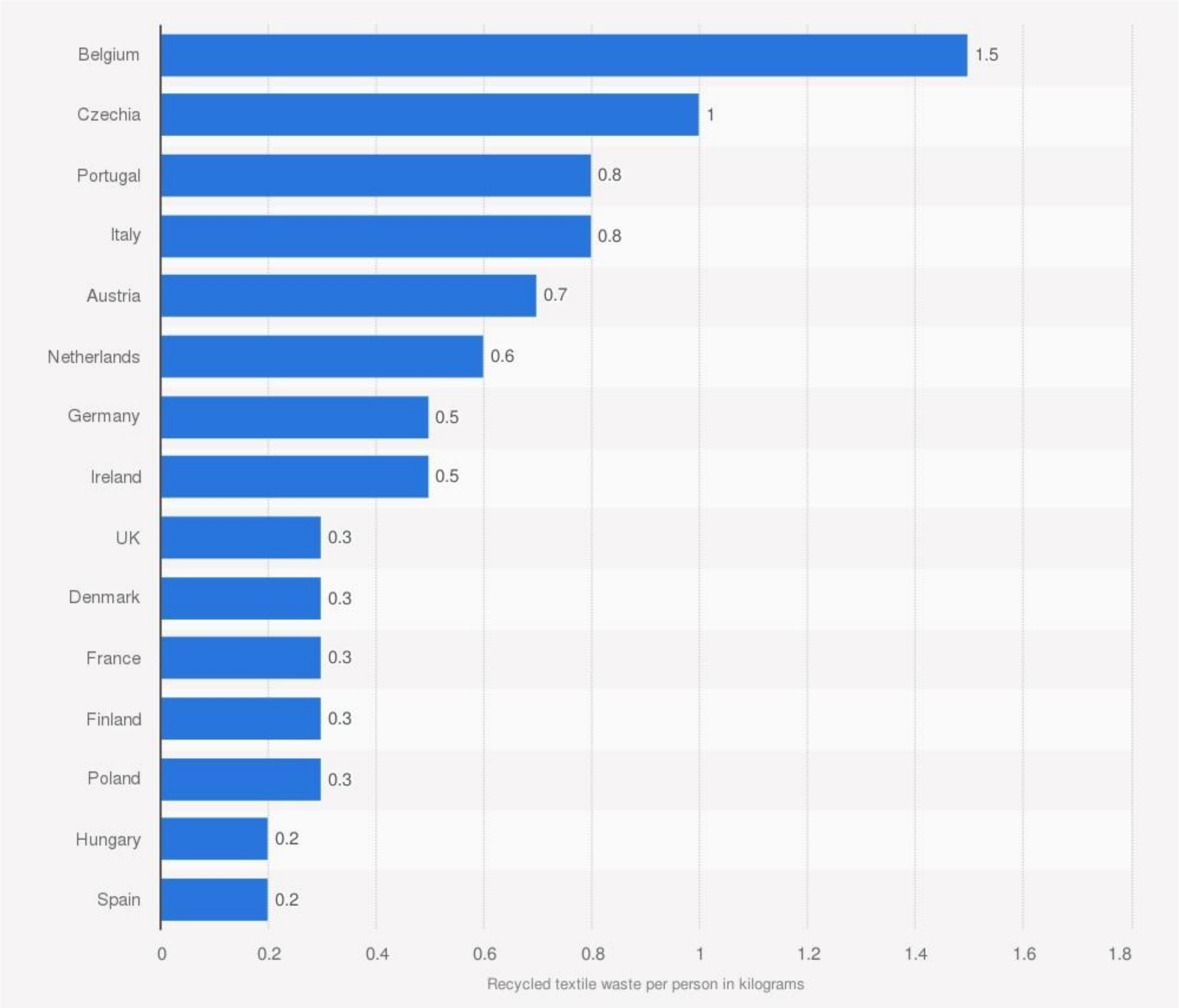

Figure 4*. The EU's annual recycled textile waste production, subdivided by country, in 2016 (kg).*

(Source:https://www.statista.com/statistics/1090566/textile-waste-generated-in-the-european-union-per-person/).

One of the most critical initiatives for the European Union is the transition to a circular economy. The EU prioritizes investing in a circular model as an alternative to the current one, a linear model based on the "production-consumption-disposal." Reusing, rejuvenating, and recycling existing materials and goods becomes the emphasis of a circular economy, which highlights using waste as a resource (Tedesco & Montacchini, 2020).

2.2 Textile Industry in Italy

The textile industry ranks third among the most profitable industrial sectors in the country, and Italian fashion is regarded as a benchmark of excellence (Tedesco & Montacchini, 2020). According to estimates issued by Sistema Moda Italia (SMI), the employers' organization for the Italian fashion and textile industries, the total income of the whole industrial sector is anticipated to reach €54.1 billion in 2017[5]. On the other hand, a recent survey from sustainable fashion business LABFRESH underlines that Italy is Europe's top polluter of textiles, creating 466 tonnes of textile waste annually and 7.7 kilos of textile waste produced per person[6]. The brand also discovered that Italians spend a significant amount on new clothing each year, at €1080 per person.

Furthermore, international policies promoting the circular economy may be a leader in innovation and an opportunity for many industries, notably construction. Towards a circular economy model for Italy, issued by the Italian Ministry of the Environment, highlights the strategic relevance of the construction sector in developing an economy where sustainable resource usage and waste use are the keys to a new development model (dell'Ambiente, n.d.). Italy has implemented Minimum Environmental Criteria (CAM), which are public policy measures to promote recycled materials and materials with a low environmental effect throughout their life cycle.

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[5] https://ww.fashionnetwork.com/news/Italian-textile-and-fashion-industry-set-to-exceed-revenue-forecasts-for-2017,975041.html

[6] https://www.fibre2fashion.com/news/textile-news/italy-worst-textile-polluter-in-europe-uk-4th-study-254591-newsdetails.htm

Although charities and voluntary take-back initiatives dominate the collecting of post-consumer textiles, it is still limited. Figure 5 shows that despite a consistent trend in 2016 and 2017, a separate collection of post-consumer textile wastes has developed in Italy. In 2018, Italy collected around 146 kilotons of textile waste, referring to a 10% increase over the previous year, when 133 kilotons were gathered around the country. This trend shows a growing awareness of the need for waste recovery to reduce negative environmental and health impacts (Rubino, 2021).

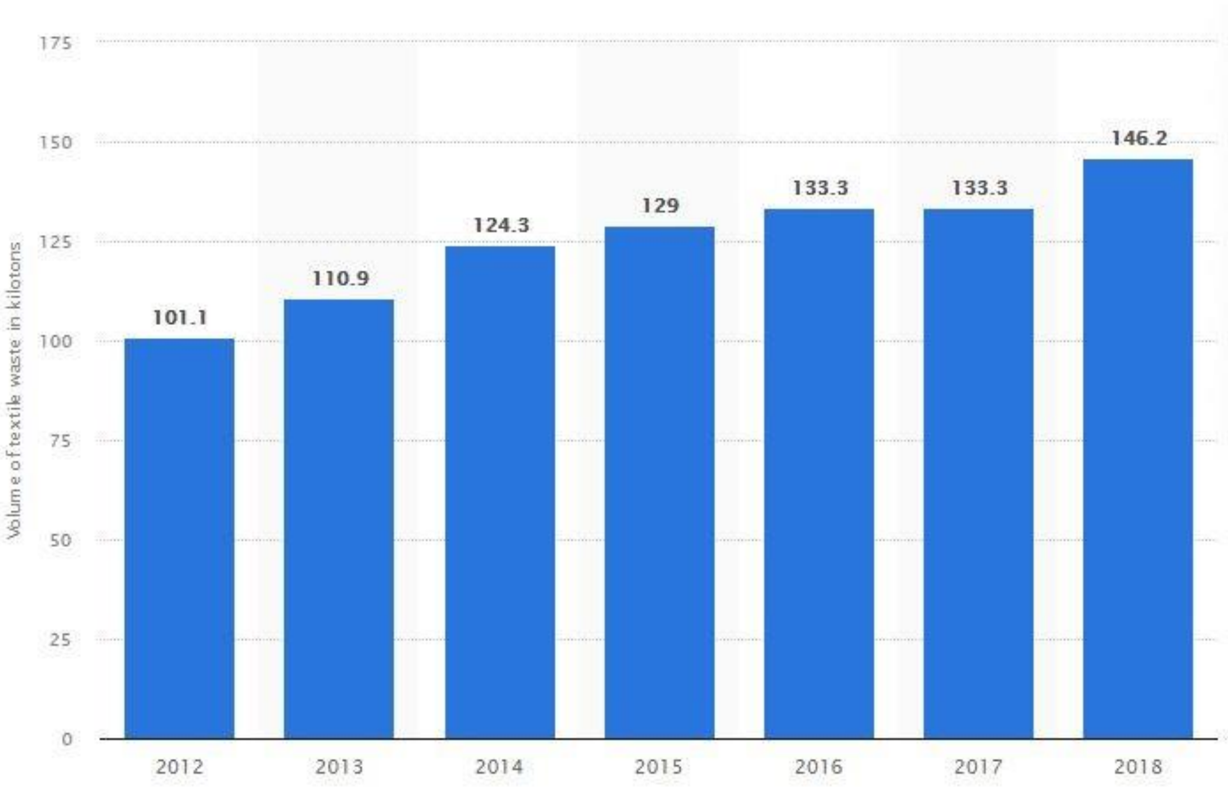

Figure 5. *The volume of post-consumer textile waste separately collected in Italy from 2012 to 2019 (Source: https://www.statista.com/statistics/910443/volume-of-textile-waste-collected-in-italy/).*

2.3 Textile Waste from Fashion Industry

The fashion system is constantly introducing new models of popular things while simultaneously encouraging the obsolescence of older ones. Therefore, textile waste has become a significant issue in the fashion industry and an undesired but inevitable scenario. Textile leftovers occur throughout the supply chain, customer usage, and end-of-use disposal, generated at all stages of textile production, from textile manufacture to garment production to customer service, and it takes various forms (Mifetu, 2021).

As one of the world's most significant consumer industries, the fashion industry, with €1.5 trillion in revenue in 2016, needs to address its environmental footprint. The earth's natural resources are being exhausted, and the fashion industry is a key contributor. With precious resources becoming increasingly scarce, the industry will confront growing expenses across the board, from materials to energy. In the Sustainable Fashion Summit on 1 February 2019, the United Nations Economic and Social Council President stated that sustainable fashion is crucial to achieving the 2030 Agenda. Otherwise, these challenges will threaten industry growth itself (Jacometti, 2019; Kerr & Landry, 2017).

The fashion industry must play a critical role in the transition to sustainability and the circular economy because of its significant environmental, climatic, and social impacts. Since it has an extensive and sophisticated supply chain, it is considered one of the most polluting industries and consumes the most water. Specifically, the textile and fashion industry emits 3.4 million tonnes of greenhouse gases yearly, utilizes 6–9 billion liters of water, and uses 6 million tonnes of chemicals, according to SMI (Sistema Moda Italia). Besides, Kerr & Landry 2017 states that the sector's waste production would climb by 63 percent by 2030, increasing CO_2 emissions. However, if the fashion industry addressed its environmental and social issues, the world economy would gain about €160 billion annually (Kerr & Landry, 2017).

2.3.1 Fast fashion: mass waste production

Numerous trends can contribute to over-consumerist behavior. The concept of fast fashion is based on mass manufacturing, low pricing, and high sales volumes. Clothing prices have decreased relative to inflation during the last decade, and each item is worn less frequently than in the past (Zhongming et al., 2019). Besides, the number of new apparel collections issued by European clothing businesses per year has increased from two in 2000 to five in 2011. For example, Zara has 24 new apparel collections every year, and H&M has 12-16. Consequently, the fashion cycle renders styles outmoded before the clothes reach their actual end of life in the textile industry, resulting in waste and excessive consumerist activities (Sajn, 2019; Slater, 2003).

The exponential growth in the manufacturing and consumption of (fast) fashion has caused a spike in textile waste. Historically, Western countries dealt with textile waste by exporting used clothing to underdeveloped countries, particularly Africa. However, as waste production increases, such an approach cannot remain, as many developing countries like Turkey and China prohibit the import of textile waste, either to protect domestic production (Anguelov,

2015) or because markets are overloaded with second-hand clothing, which has displaced domestic production as in parts of Africa (Brooks & Simon, 2012).

Circular thinking (expanding and intensifying usage and reuse, redesigning, and recycling waste) requires fewer resources than today; protects the environment and water; achieves low carbon use; consumes less energy; and uses fewer virgin materials (Stahel, 2017). WRAP (2012) calculated the impact of increasing the life of garments. According to WRAP data, the average lifespan of a garment in the United Kingdom is 2,2 years. As illustrated in Table 1, even a minor alteration in customer behavior can impact. For instance, a 9% reduction in waste in the United Kingdom would reduce 150 000 tons of waste.

Table 1. *The effect of extending the use of garments (Source: WRAP, 2012, 23)*

Extending the use with	Carbon-saving	Water-saving	Waste-saving
10% = 3 months	8%	10%	9%
33% = 9 months	27%	33%	22%

There are two strategies for reducing textile waste and implementing more sustainable fashion practices: proactive (prevent, minimize) and reactive (reuse, recycle, and disposal). In modernizing the fashion sector, proactive waste avoidance requires unique design–production–marketing logic. Effective waste reduction requires a combination of proactive and reactive strategies that reduce waste while reusing products. This innovative approach to garment production might save up to 17% virgin material and 7,927 kg CO_2 per 10,000 garments produced. Small offcuts can be employed in mechanical fiber recycling, saving more fabric and reducing CO_2 emissions. Creative manufacturing strategies could help lessen the garment industry's environmental effect. Closer collaboration between design and manufacturing may also lead to a new low-waste design–manufacturing–consumption model (Niinimäki, 2018).

2.3.2 Environmental impacts of the textile waste

In comparison to other businesses, the garment industry has a particularly complicated supply chain that is related to a variety of sectors, including the fossil-chemical industry (for synthetic fibers), the wood sector (for cellulose-based fibers), and the agriculture sector (for animaland plant-based fibers). Complete traceability to suppliers is limited due to the sometimes long and complex supply chain. Consumers and other stakeholders have generally put slight pressure on companies to improve supply chain traceability. As a result, when it comes to statistics on production and consumption, as well as their associated emission profiles, the industry falls behind other sectors.

Although the exact amount is unknown, it is apparent that the industry's contribution to global greenhouse gas emissions is substantial and expanding rapidly. Companies and stakeholders must establish aggressive climate goals, shift into action, and restructure their business models.

Incontrovertibly, if garment production and consumption continue on their current paths, expanding by another 63%, fashion's environmental impact will continue to add to the planet's negative consequences (Kerr & Landry, 2017). From the first stages of manufacture (pre-consumer waste) until the completion of its useful life (post-consumer waste), a textile fabric can contribute to pollution. The textiles system generates resource inputs, environmental and climate strains, and impacts at every stage: from fiber production to distribution and retail, textile usage, collection, sorting, and recycling, and ultimate waste management (Zhongming et al., 2019).

Table 2*. Significant environmental concerns are associated with product life-cycle stages (Source: Koszewska, 2018).*

Environmental Problems	The most impactful stages in the product life cycle
Resource use	Production of manufactured fibers, yarn manufacturing, finishing processes, the washing and drying of clothes in the use phase
Water and chemicals use	Fiber growth, wet pre-treatment, dyeing, finishing and laundry
Land use	Excessive use and contamination of the forest lands for cultivation
Greenhouse gases emission	Transportation within globally dispersed supply chains
Waste generation	Notably, product disposal at the end of its service life, textile/clothing production

To better assess the extent, context, and opportunity associated with each area of environmental impact, it is beneficial to examine them. Table 2 summarizes the ecological problems and most impactful stages in the product life cycle.

Resource use

Clothing, footwear, and home furnishings constitute the fourth largest pressure category in terms of total primary raw material usage in the supply chain for consumption in the EU. The manufacturing of raw materials accounts for a sizable portion of the textile and garment industry's environmental effect, not least due to cultivating crops for natural fibers. To manufacture and manage all apparel, footwear, and home textiles purchased by EU-28 householders in 2017, a projected 1.3 tonnes of primary raw materials, approximately 85% of them, were used (Zhongming et al., 2019).

Water consumption

Currently, the fashion sector consumes over 79 billion cubic meters of water, enough to fill nearly 32 million Olympic-sized swimming pools. GFA and BCG predict a 50% rise in water demand by 2030. Besides, the gap between water demand and supply is expected to widen to 40% by 2030. As water shortage worsens, cotton-growing countries and the fashion industry may be forced to choose between cotton output and safe drinking water (Bank, 2016).

Land use

Clothing, footwear, and domestic textiles are the second-highest land use stress category after food consumed in the EU. Most land-use pressures (93%) originate from outside the EU and are caused by cotton farming (Zhongming et al., 2019).

The extent of cleared forest land for diverse uses, including cotton farming, has surpassed the safe operating space by 17% (Rockström et al., 2009; Steffen et al., 2015). By 2030, the fashion industry will have taken over 115 million hectares of land that might be utilized to cultivate crops for a growing population or to conserve forests (Bank, 2016). This is a tremendous incentive for the fashion sector to think about its raw materials' environmental effect and to change its material mix. Stricter restrictions on non-food crop access may result from lacking agricultural land (Kerr & Landry, 2017).

Water contamination caused by chemicals

Textile manufacturing uses a vast number of chemicals. Textile manufacture uses over 3500 chemicals. Seven hundred fifty of them are dangerous to human health, and 440 are detrimental to the environment. Dyeing and polishing textiles pollute water, impacting worker and community health. Washing discharges chemicals and microplastics into drains. Plastic microfibres are predicted to be discharged into the ocean every year by washing plastic-based garments (Zhongming et al., 2019).

Greenhouse gas emissions

In terms of climate change, textile production creates 15-35 tonnes of CO_2 equivalent for each tonne produced. This value chain is the fifth most significant contributor to greenhouse gas emissions in the EU (Kerr & Landry, 2017). In 2017, the manufacture and processing of clothes, footwear, and home textiles created 654 kg CO_2 equivalent per person in the EU-28. 25% of this occurred within the EU-28 (Zhongming et al., 2019).

According to recent earth system studies, atmospheric CO_2 levels are already 20% over acceptable levels (Rockström et al., 2009; Steffen et al., 2015). Several key fashion production regions are particularly vulnerable to climate change and increasing sea levels, so the global economy and fashion industry suppliers stand to profit greatly. Processing has the most extensive influence on the climate, followed by garment usage and raw material production (Strauss, 2017).

Generation of waste

Humanity is currently putting pressure on the biosphere by producing 2.1 billion tons of leftovers annually. The global population presently creates more than 1.6 times the annual ecological imprint that the earth can absorb. Because of using today's solid waste throughout production and end-of-use, the industry's waste will grow by around 60% between 2015 and 2030, generating an extra 57 million tons yearly. This amount takes fashion trash to 148 million tons in 2030, or 17.5 kg per person. (Kerr & Landry, 2017).

The international economy will benefit significantly if the fashion industry successfully recycles textile waste into raw resources. Nevertheless, this technique is not accessible for all fibers and has not been shown commercially feasible at scale. It is estimated that the global economy might save roughly €4 billion per year by 2030 if manufacturing and consumption were more circulars (Kerr & Landry, 2017).

2.4 Textile Waste Management in European Union

In Europe, approximately 15-20 percent of waste textiles are collected, whereas the remaining is landfilled or burnt, about 50 percent of collected is downcycled, and the other 50 percent is reused, primarily by exported to East European or African nations. Because textile recycling is limited today, most of the flow is downcycled into wipes, rags, or utilized as insulation in other sectors.

The rest is either landfilled or burned. In certain circumstances, unused clothing is stored in closets or exchanged among friends or family (Palm et al., 2014). Textile waste management varies widely within the European Union (EU). In certain countries, such as Sweden, textile waste is treated by incineration with energy recovery. Textile waste collected in containers and bags is incinerated with other municipal refuse. The recovered heat and power might replace other energy sources (Zamani, 2014). There are, however, substantial variances within Europe: more noteworthy examples are Germany, in which roughly 70 percent of waste textiles are collected for reuse and recycling, of which a percentage is segregated for incineration (Sandin & Peters, 2018). In Denmark, over 50% of waste is collected for domestic or international reuse (Palm et al., 2014). Nonetheless, there is a significant opportunity to boost reuse, as clothing items are often discarded far before the end of their technical service life (Roos et al., 2017; Woolridge et al., 2006).

In the 2017 interinstitutional talks on the Waste Directive, European Parliament strongly supported textile recycling and suggested that by 2020, all Member States must have distinct textile collections. While the separate collection's requirement was included in the final directive, the timeline was pushed out to 2025 during talks with the Council (Sajn, 2019).

Furthermore, according to the estimates, EU members purchased 6.4 million tonnes (12.66 kg per person) of new apparel in 2015 (Sajn, 2019). This is why it is essential to change the ways European consumers use their clothes. From the consumers' point of view, the European Union's objectives refer to increasing consumer awareness, ensuring transparency and environmental labeling, and improving washing and drying instructions (Sajn, 2019).

Consequently, despite the difficulties of waste generation growing in prominence in recent decades, waste management is the principal effort to safeguard the environment in modern industrial civilization. Reduced waste flowed to landfills, increased waste reuse (Marino et al., 2017), and raised consumer awareness have been necessary to mitigate the waste impact on the environment.

2.4.1 Sustainability policies in the fashion sector

Global manufacturing processes are increasingly split into complicated supply chains with several actors, subcontracting, and illegal activities. The textile industry leads one of the most challenging production methods. In the supply chain, involving design, manufacture, fashion items (such as textiles, clothes, footwear, leather, and fur products), distribution, and retail to ultimate customers, transparency and traceability are vital in the fashion industry's journey towards more sustainable production and a circular economy (Jacometti, 2019). On the other hand, the textile and garment business is a high-embodied energy system with a substantial environmental impact at every level of the supply chain (Echeverria et al., 2019).

Ratti SpA, an Italy-based company specializing in the textile industry, pursues a sustainable policy and aims to reuse and recycle fabric wastes by minimizing consumption. According to the Sustainability Report by Ratti Group 2020[7], "Second Life Fibers" is one of three enterprises of "Second Life" platforms (the other enterprises are "Second Life Print" and "Second Life Hydro.") established by Ratti SpA to achieve the design and development of circular products.

2nd Life Fibers specifically uses silk waste for lining for finished clothing, aiming for product longevity and recycling. The lining from 2ndLife Fibers is 70% silk and is available in five different weights (Ratti SpA, 2020). Due to the unique properties of the raw material, silk as a natural fiber is resistant and lightweight and has remarkable thermal, breathability, and hygroscopic properties. Subsequent technological and transformation processes resulted in a high-performance thermal insulation ideal for use as a lining for outdoor and casualwear garments. The air-laid technique and the three-dimensional form that emerges from it enable the development of many microscopic air pockets, which provide superior breathability and thermal qualities to silk strands.

"2nd Life Fibers," in collaboration with ITC, an ONU agency, started up the Ethical Fashion Initiative programs to enhance environmental performance during manufacturing. Moreover, circularity means that waste stops being waste (the end of waste) and is generated into a secondary raw resource according to the company's environmental strategy. The Sustainability Report of Ratti Company 20205 highlights that "Italy is not a primary raw materials country, but it is a secondary raw materials country. And this is our wealth.".

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[7] https://www.ratti.it/en/sustainability/sustainability-report/

2.4.2 Textile leftovers recycled in various fields

Textile recycling, which frequently refers to converting pre-or post-consumer textile waste, can be a way to create textile or non-textile products. Textile waste has several interesting possibilities in various sectors, including the automobile industry, construction, and energy.

For instance, some companies specialize in managing the recycling rates of clothing brands. I:CO is a Swiss solution provider specializing in recycling solutions. It collaborated with H&M in 2017 to boost the fashion brand's "Bring It" campaign. It gathers people's unwanted shoes, belts, bags, and apparel at collection stations located around Europe. It collaborates with over 60 retailers, including The North Face, Levi's, Forever 21, Intimissimi, Reno, Adler, C&A, and Esprit. They arrange for transporting, sorting, and recycling donated textiles, establishing the infrastructure necessary for raw materials to enter a closed-loop manufacturing cycle.

Other firms are creating more sustainable fiber combinations and materials, such as Lyocell and Tencel, which will be utilized to manufacture denim, underwear, casual clothing, and towels. Additionally, Lyocell can be combined with a range of other fibers, including silk, cotton, polyester, linen, nylon, and wool. It can be used to create the appearance of suede, leather, and silk. Lenzing Group manufactures the cutting-edge Refibra branded lyocell from the cotton waste collected throughout the value chain.

In addition to the above-referenced companies, Clarisse Merlet founded FabBRICK as a young architect aware of the environmental importance of both the construction and fashion industries. FabBRICK's mission is to decrease textile waste and explore new building strategies using novel construction methods. FabBRICK is also the product's name, the world's first brick entirely made of recycled textiles and offers promising capabilities as an insulator, an aesthetic, and a load-bearing structure. In that context, FabBRICK could be used in various interior design projects, including seats, walls, and retail furniture.

There is a growing trend toward adopting safer and healthier material inputs that enable recycling and minimize negative impacts during the manufacturing, usage, and after-use phases.

3 CIRCULAR TEXTILE AS BUILDING MATERIAL

The linear economy model exhibits a consumption and resource use pattern rendering the ecosystem unsustainable with the conventional take-make-waste practice (Figure 6).

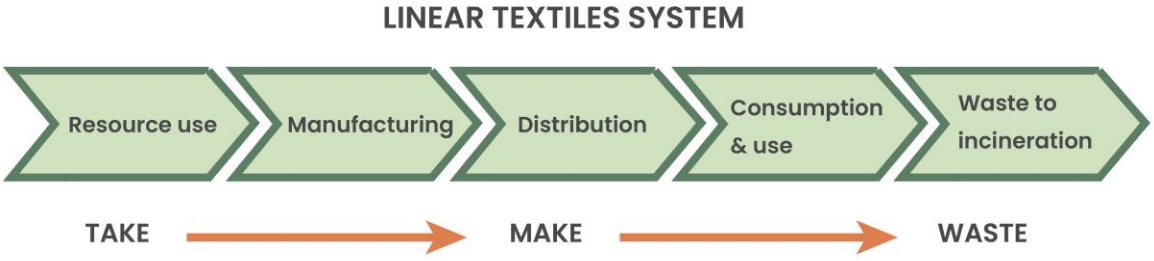

Figure 6. *Illustration of linear textile system (Drawn by the author)*

According to the European Commission (2015), the circular economy is defined as the practice of preserving the value of products, materials, and resources for as long as feasible while minimizing waste. This concept promotes the extended use of natural resources to mitigate future access to primary resources and waste creation. Hence, the circular economy is a multi-dimensional concept with multiple fields of action: first, the priority in waste management, with landfill disposal as an extreme ratio; second, the enhancement of by-products and waste with the production and use of new raw materials (end of waste); third, the focus on the production phase and the transition to a sustainable bio-economy model using renewable raw materials. Shortly, the circular economy model is "formed by the 3R (reduce, reuse, recycle) principles, which should be followed throughout the whole cycle of resource generation, consumption, and return." (Jacometti, 2019).

A circular economy approach in the fashion industry entails encouraging the use of eco- and sustainably-sourced raw materials while also supporting the extension of the valuable life of textile and garment goods through recycling and repurposing (Figure 7). Incorporating textile wastes into a novel production process might result in contributing to the circular economy model. This is a precious strategy for achieving a sustainable environment through waste reduction and increased added value from new goods (Rubino et al., 2018).

Figure 7. *Circular textiles system for sustainable waste management (Drawn by the author)*

Besides, the European Commission defined a circular economy priority product category for textiles in 2019's Sustainable goods in a circular economy: Towards an EU product policy framework for the circular economy (Zhongming et al., 2019).

3.1 Using Textile Waste as a Resource

The textile industry is one of the new circular economy action plan's core product value chains, focusing on resource-intensive industries with significant circularity potential. Many private and public sector organizations recognize the potential benefits of a circular textiles system.

As stated previously, wastes generated by the textile system are classified into two categories: pre-and post-consumer wastes (Rubino, 2021). Payne (2015) highlights that pre-consumer scraps generated from cutting and sewing garments accounted for roughly 15% of the total fabric required to produce each item. At least 75% of pre-consumer waste could be recycled. Additionally, multiple environmental advantages may arise from reusing and recycling pre-consumer or post-consumer textiles waste. For example, reusing textile and apparel goods results in energy savings since the energy required to collect, classify, and resale used clothes is ten to twenty times less than the energy necessary to manufacture the same products from virgin materials (Fletcher, 2008). Additionally, several international studies have used Life Cycle Assessment (LCA) to assess the textile industry's environmental consequences and suggest mitigation measures. Within the recommended methodologies in these studies, research has demonstrated that post-consumer solutions for recycling and reusing worn clothing can avoid or reduce the manufacture of new garments (Moazzem et al., 2018).

Circular business concepts for textile creation, sharing, recycling, and reuse have recently emerged. Upscaling such business models requires a systemic transformation enabled by law and other policies (Zhongming et al., 2019). Textile sorting, reuse, and recycling through innovative industrial uses and legislative initiatives such as expanded producer responsibility should be encouraged (Tedesco & Montacchini, 2020).

3.2 Recycling Methodology: Shift to Reusing, Recycling, Upcycling

Textile wastes might be regenerated in a circular economy and industrial symbiosis within a new manufacturing cycle (Tedesco & Montacchini, 2020). There are three methodologies to recycle textile waste to maximize its life cycle duration.

The first methodology is textile reuse which is a strategy that encompasses transferring textile items to new owners to extend their service life, with or without alteration. (Fortuna & Diyamandoglu, 2017). Second-hand stores, flea markets, garage sales, internet marketplaces, charities, and clothes libraries are all examples of sites where this might be realized (Sandin & Peters, 2018). This can be conceptualized as collaborative consumption or commercial sharing systems (Belk, 2014). Besides, apparel and household textiles can be downcycled into various textile-based products such as rags, low-grade blankets, and upholstery (Gardetti & Torres, 2013).

The second methodology is textile recycling, covering two categories: recycling during the manufacturing process and outside the manufacturing process. The first category concerns the repurposing of textile wastes as raw material for products with a similar manufacturing process to textiles, namely home furnishing goods. The second category, recycling out of the manufacturing process, refers to the repurposing of textile wastes as new raw materials in another manufacturing process, e.g., developing composite materials for the construction sector (Zonatti et al., 2016).

The last methodology is upcycling, which is the creative process of recycling clothing and textile waste into new garments and items by reusing deadstock or leftover fabric. It is significant in terms of sustainability, waste reduction, and industrial pollution. Indeed, creativity and innovation are essential words during the upcycling operation because reusing an object to a higher value requires a creative mind, aesthetic sensibility, an inventive look, and knowledge that is quite different from a standard design approach. A sophisticated level of aesthetics elevates the value of repurposed materials. In this research study, upcycling strategies will be attempted to generate unique architectural implementations and interior products by utilizing different types of textile waste.

3.3 Upcycled Textile Fibers for Sustainable Building Materials

Traditional buildings require enormous amounts of energy and raw materials during their lifespan, construction, and destruction phases. On the other hand, eco-friendly products manufactured from secondary raw materials have been vital since excessive use of raw materials will result in resource shortages for future generations (Nautiyal et al., 2015). Indeed, environmental impacts and raw material demand associated with the building industry need to be minimized to define a more feasible, sustainable, and circular economy.

As Agrawal et al. (2013) highlight that 95% of textiles are recyclable, textile waste has enormous reuse and upcycle potential, as evidenced by research and uses in various industries, including automotive and eco-design. Also, recent applications have demonstrated the potential to reuse leftover textile scraps as sustainable raw resources in the construction industry, mainly mechanical, hygrothermal, and acoustic aspects of new building materials with higher performance than conventional construction materials (Rubino et al., 2018; Tedesco & Montacchini, 2020).

Furthermore, the first research on using textile waste for construction materials was published in 2003, making it a current practice. The graph in Figure 8 demonstrates that the interest in textile construction materials has grown since 2012, and many experimental findings have been published since 2014 (Rubino et al., 2018). Besides small and medium private companies, some entrepreneurs have successfully applied textile waste in the construction sector.

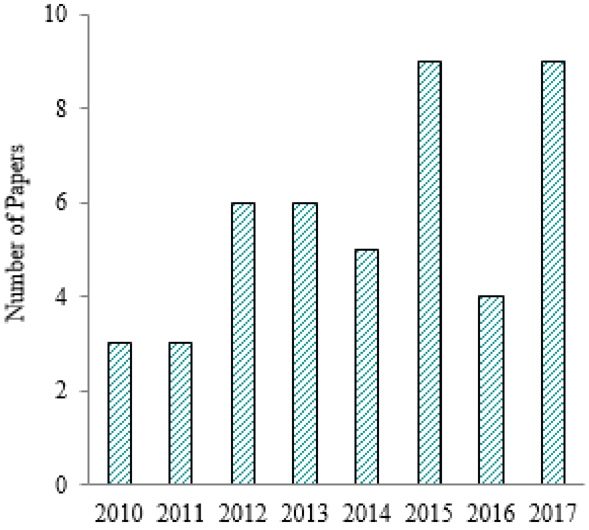

Figure 8*. The number of articles published per year (Source: Rubino et al., 2018).*

3.4 Recent Textile Waste Applications in the Construction Industry

In the recent decade, an increasing number of research projects have been conducted to use textile wastes as new raw materials having superior hygrothermal and acoustic properties. The research papers have revealed the great use of textile fibers, primarily as the matrix of panels in the form of matting or paneling, energy-efficient bricks, innovative concrete or plaster mortar, and reinforcement material of lightweight bricks or cement-based facades (Rubino, 2021). In the case of mortar and render, waste yarns might serve as an acceptable substitute for reinforcing steel. Recycled fibers as reinforcement in composites can be utilized for various purposes. Increasing the use of those composite materials has several advantages (Todor et al., 2019). Apart from being lightweight, natural-based reinforced composite materials may be formed into complex shapes and structures. Besides, they are biodegradable, cheap, relatively available, and have moderate mechanical performances compared to synthetic fibers.

3.4.1 Recycled textile fibers converted into thermal and acoustic insulation

Textile materials are crushed or chopped and repurposed in the manufacture of added–value goods, including sound insulation and thermal insulation materials (Todor et al., 2019). However, they may also be used to enhance some specific traditional materials' acoustic or thermal performance (Rubino, 2021), such as combining textile waste with cement, lime, water, bricks, and other building materials in a suitable ratio (Islam & Bhat, 2019).

Acoustic Performance

Bio-based fiber materials are the most suitable acoustical solutions because they are more economical, lightweight, pollution-free, and have excellent sound absorption capacity (Zhu et al., 2014). For instance, as the diameter of bamboo fiber decreases, the sound absorption coefficient increases. Energy loss rises with increasing surface friction as the number of fibers per unit area increases (Koizumi et al., 2002). Natural fibers are also porous materials that comprise numerous linked air cavities, which may be the primary contributors to sound energy absorption (Yang & Li, 2012).

Mar Barbero-Barrera et al. combined textile waste with natural hydraulic lime to create sound and heat insulating. Initially, industrial textile wastes (mainly cotton) were collected and blended in three different ratios with natural hydraulic lime and water. After many days of curing and drying, the samples were evaluated. Del Mar Barbero-Barrera et al. measured the best thermal conductivity of 0.14 (W/mK), which is much less than the 0.189–0.277 W/mK of a comparable wood–gypsum board. However, the acoustic absorption coefficient was around 0.2 at 2000 Hz, which is relatively low.

Patnaik et al., 2015 investigated the sound insulation capabilities of needle-punched waste wool and recycled polyester fibers (r-PET) for industrial applications. Needle-punched mats made of waste wool and r-PET fibers were tested for acoustic performance.

Thermal Insulation

Several researchers produced thermal insulation materials by directly cutting textile scraps and stitching the wastes. Trajković et al. (2017) cut polyester clothes to form insulation structures. Three types of polyester woven clothing were gathered and cut into tiny species using rotary blades and a vertical knife.

Sedlmajer et al. investigated the thermal conductivity of insulation mats made of recycled polyester, cotton, and bicomponent fibers in various compositions. Mats with a unique cotton fiber content were shown to have superior insulating qualities (Sedlmajer et al., 2015). Binici et al. synthesized lightweight composite materials from cotton waste and fly ash, observing that composites with a more significant proportion of cotton waste had a higher thermal conductivity (Binici et al., 2012). On the other hand, (Raftoyiannis, 2012) uses cotton, a plant-based fiber, to replace conventional fiber such as glass fiber and carbon fiber in reinforcing plastic materials, and experiments the composite panel is reinforced with cotton fibers. Three types of cotton fibers, untreated cotton, treated cotton, and cotton textile, were examined by mixing with polyester resin as a binder to produce the specimens in this study. The tests have shown that the cotton textile's tensile performance is relatively lower than the untreated and treated cotton. However, it demonstrated that absorbing moisture reduces the material strength of treated and untreated cotton fibers while increasing the strength of the textile fiber. The findings of this study indicate that cotton fiber composites exhibit good structural performance for structural components with minimal requirements, such as wall panels or doors.

3.4.2 Upcycling textile as a novel material composition

Recently, discarded textiles have been used in brick form for low-performance requirements relatively for interior applications. French architect Clarisse Merlet and her studio *FabBRICK* have been recycling discarded textiles into an insulating, structural, and aesthetic building material since 2009. The applications of the studio are based on furniture and partition walls (Figure 9).

Innovative products in Figure 9 show the architectural products of *FabBRICK;* figure a shows a brick sample made of fabric scraps, figure b illustrates an interior wall covering made of fabric waste bricks, and figure c exemplify interior furniture implementations of products by using FabBRICK waste bricks.

***Figure 9**. Construction material made of recycled textile by FabBRICK*

(Source:https://www.greenqueen.com.hk/fabbrick-meet-french-architect-clarisse-merlet-who-converts-your-old-clothes-into-bricks/).

The production process of the fabric bricks is entirely mechanical. Post-consumers fabric wastes are shredded in 3 different sizes 7 mm, 20 mm, and 40 mm. The following step is the preparation of the starch-based glue in 100% made of ecological ingredients without the use of chemicals. The fibers and glue are combined, compressed in a mold, and resulting in the form of a brick. Later, the brick dries in ambient air between 10-15 days. Consequently, a material with extremely high mechanical resistance is created comparable to a concrete block. On the other hand, it has an excellent insulating quality, both acoustic and thermal, and a high resistance to fire, in addition to being resistant to water, although only when used inside (*Fabbrick Projects*, n.d.).

Wendy Andreu has devised a new strategy to ensure the company's waste is sustainable and blended the wasted fibers with a water-based, solvent-free acrylic resin to make a durable, multifunctional product (Figure 10). The finished product is versatile; it may be poured into molds, used to cover an existing form, or combined with other media to create fascinating textures (Lusiardi, 2019).

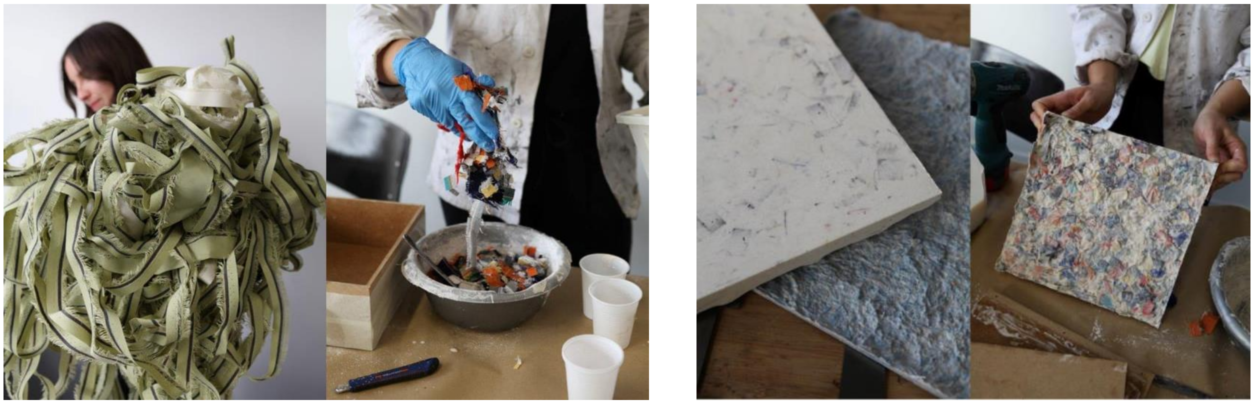

***Figure 10**. The textile scraps experiments mixing with a glue (a), textile-waste-based products (b)*

(Source: https://www.inexhibit.com/marker/sunbrella-and-wendy-andreu-sustainable-design-from-textile-waste/).

In recent decades, the recycling of denim fibers has been widespread in the building industry. Specifically, several companies have been reusing jeans leftovers by processing them mechanically with minimum waste and performing them as insulation or plaster material. In this way, recycled cotton can be utilized as it is or blended with new cotton to use as a raw material in denim manufacture (Voncina, 2016). Moreover, each kilogram of cotton that is not burnt saves the environment 3.1 kg CO_2, 45MJ energy, and roughly 7000 liters of water (*DenimX Products*, n.d.).

One of the most successful applications of denim waste as an insulator has been realized by an Arizona-based company called Phoenix Fibers since 2011 (Figure 11). Phoenix Fibers turns about 975 tons of denim and other cotton fabric each month into a shoddy fiber, subsequently produced into various goods. Denim insulation is used in homes and workplaces, appliances, and vehicle insulation (*Phoenix Fibers*, n.d.).

Figure 11. *Wall panel made of recycled jeans fibers (Source: https://www.denimx.nl).*

A second good example is the recycled denim plaster which consists of waste denim strands lengthened for an appealing appearance. The fibers are combined with a biodegradable adhesive to form a thick paste known as textile plaster. Sheets are pressed from our carefully developed formula of textile fibers and bio-based polymers that may be molded into three-dimensional items on a big scale. In order to have a completely circular material, water can be used to remove the material from the wall. After removing the fibers, they can maintain their binding characteristics. If multiple major denim brands agreed on the same strategy, a large enough denim recycling market might be created.

4 TEXTILE UPCYCLING EXPERIMENTS FOR A NOVEL BUILDING MATERIAL

The work illustrated in the following research study demonstrates the materials and methods selected to produce the upcycled textile samples. A brief overview of the textile fibers (i.e., silk, cotton, viscose) as the base matrix with the binding agents (i.e., starch-based binders, casein-based binder) is described to comprehend their nature and potential use for potential use in the building sector.

4.1 Characteristics of Experiment Materials

The experimental upcycling process is included three types of textile fibers as base matrix and two types of bio-based binders. The base matrixes of the experiment, including 100% silk, 100% cotton, and 100% viscose, are provided by the Italian textile-based company "Ratti SpA," having strong sustainability policies. The binding agents are a starch-based binder and, casein-based binder, and they are produced in the SAPERLab, which belongs to the 'Material Balance Research Group' in Politecnico di Milano. Both binders are 100% handmade production and consist of complete bio-based materials to provide the adhesive property of the blend composition. Bio-composite materials' low embodied energy represents a substantial potential advantage for lowering the environmental effect of construction goods, and natural-based ingredients offer a lightweight, biodegradable, and low-cost composition.

4.1.1 The properties of textile fibers as a base matrix

The base matrix materials of experiments are defined using organic textile fibers because adding organic fibers decreases heat conductivity, boosts mechanical strength, makes composites lighter, and causes lower environmental impacts. In other words, more fibers mean less weight, less thermal conductivity, and less specific heat (Onésippe et al., 2010). The physical and chemical properties, advantages and disadvantages, and production processes of silk, cotton, and viscose are explained.

4.1.1.1 Silk Fiber

Silk, 'the queen of fibers,' is grown in the fine strand rather than hair. It is more than a textile fiber; it is a biopolymer made up of two protein molecules called fibroin and sericin (Cosetex, n.d.-a). Silk has numerous advantages such as having low density, moderate stress, good raw material in terms of ecological impact, high compressibility. Continuous filament fibers such as silk are frequently the ideal reinforcing material substitute (Shah et al., 2014).

Silk fibroin is a natural protein with a semicrystalline structure giving strength and stiffness to the fibers. The polymer is the main component of silk with 80% of mechanical strength. The sericin binder holds the fiber structure together by acting as an adhesive binder (Morin et al., 2016).

Silk production consists of 3 main processes: reeling, throwing, and degumming. It starts with reeling to unwind the filament from the cocoon in the boiling water by softening the sericin gum. The second step is throwing, combining, and twisting the multiple strands to shape a heavier thread. The last step is degumming, which removes sericin from raw silk and has a lustrous appearance. Silks lose 20–25% of their weight in the degumming process. A higher sericin level means losing mechanical strength and stiffness. Nonetheless, degummed fibers retain excellent mechanical capabilities due to the twisted structure of the fibers. When sericin is eliminated, fibroins become aligned in loading, reducing friction between the fibers. This enhances load-bearing capability and fiber flexibility. (Mahmoodi et al., 2010).

Physical and Chemical Properties of Silk

Among natural fibers, silk is the lightest. The densities of silk fibers are 1320–1400 kg/m^3 with sericin and 1300–1380 kg/m^3 without sericin.

Tensile Strength: Silk fiber has higher tensile strength than the same thickness of steel wire and, it also does not exhibit the phenomena of yielding before breaking.

Toughness: Degummed silk fibers are equivalent in toughness to nylon and Kevlar fibers. Silk fibers have an elongation at break of between 15% and 35%, significantly more than cotton and Kevlar and equivalent to nylon.

Flexibility: Silk is very flexible, allowing the fibers to deform up to 20%-25% of their original length.

Moisture absorption: Its moisture uptake is 11%.

Heat: Silk fiber decomposes at 171°C. It has a low thermal conductivity coefficient.

Microorganisms: Silk has a high resistance against mildew and germs as long as it is not exposed to severe temperatures or humidity (Cosetex, n.d.-b).

The mechanical properties of silk fiber are compared to those of other manufacturing materials in Table 3. Silk fibers are unique in their strength and toughness, which distinguishes them from other natural and synthetic fibers. Silk fibers exhibit a distinct mechanical stress response. In general, when the rate of tensile deformation rises, the strength, modulus, and elongation at break increase. On the other hand, Silk fibers exhibit an increase in the value of the latter metric. As a result, the work required to break increases as the deformation rate increases. This suggests that silk fibers have an exceptional capacity for energy absorption at high loading rates.

***Table 3**. Comparison of chemical, physical, and mechanical properties.*
(Source:https://www.cosetex.it/wp-content/uploads/2017/05/Silk_Properties_Comparison.pdf)

	Elongation at break	**Modulus**	**Strength**	**Energy to break**
	%	**n/m²**	**N/m²**	**J/kg**
Silk – Bombyx M.	15 – 35	5×10^9	6×10^8	6×10^4
Nylon	18 - 26	3×10^9	5×10^8	8×10^4
Cotton	5.6 – 7.1	$6 - 11 \times 10^9$	$3 - 7 \times 10^8$	$5 - 15 \times 10^3$
Viscose	13	UN	UN	UN
Kevlar	4	1×10^{11}	4×10^9	3×10^4
Steel	8	1×10^{11}	4×10^9	2×10^3

(UN: Unknown)

4.1.1.2 *Cotton Fiber*

Celluloses are biodegradable, non-toxic, low density, high stiffness, superior absorption, and thermal and mechanical stability. This makes cellulose a suitable choice for high-performance structural materials (Abidi et al., 2018).

Cotton is a versatile natural fiber, the second most used fiber in the textile industry after polyester. It is the most ubiquitous type of cellulose found in nature, comprising approximately 90% (Raftoyiannis, 2012). The noncellulosic chemicals are wax, pectic substances, organic acids, sugars, and ash-producing organic salts. They are removed by chemical processing, which boosts the cellulose content of cotton fibers to almost 99%. As shown in Figure 12, cotton fiber seems a ribbon-like structure with twists at periodic in the longitudinal section (Yu, 2015).

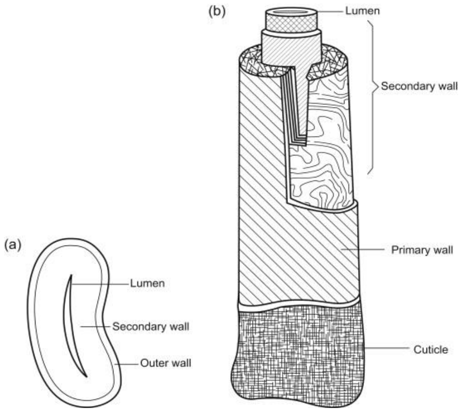

***Figure 12**. Microstructure of cotton (a) , cross-section and longitudinal section of cotton (b) (Source: Yu, 2015).*

Cotton is absorbent, soft, cool to touch, and strong as natural fiber. It has decent strength while dry but increases by 25% when wet (Fletcher, 2008). Its absorbency is due to the fiber's surface, which has a high affinity for water, the microstructure of the fiber core, resembling millions of small sponge-like tubes, and the hydroxyl (–OH) groups found in its molecules. Cotton usually has a crystallinity of 60% to 70%. More muscular and more rigid fibers have more oriented crystallinity (Yu, 2015).

The production of cotton used in clothing consists of two processes: the "spinning process" to turn raw cotton into thread and the "weaving process" to weave thread into the fabric (Figure 13). Cotton has a short life span of approximately 4-5 years. Nevertheless, manufacturing natural fibers such as cotton requires agricultural land, excessive water consumption, hazardous pesticides, and depleted fertilizers (Sandin et al., 2019).

Figure 13. *The production process of the cotton (a) Cotton fiber (b) Cotton yarn (c) Cotton weaving (Source: https://www.quilting-in-america.com/process-of-making-cotton.html).*

4.1.1.3 Viscose Fiber

Viscose is a semi-synthetic rayon fabric derived from wood pulp used as a substitute for silk. Its primary components include wood, cotton, and bamboo. The name "viscose" refers primarily to the wood pulp solution used to generate the fabric. The density of viscose ranges between 1540 and 1640 kg/m^3. The absorbent property of viscose makes it useful for several industries, such as the fashion industry. Its moisture intake is 11 – 13 %. The viscose fiber becomes weak when it is heated above 150 °C. Viscose is bio-degradable but can take 20 to 200 years to biodegrade fully. This is due to it being a synthetic material. Therefore it can be argued that it is not fully bio-degradable such as wool or 100% cotton.

Viscose was developed in 1883 as a less expensive alternative to silk. After polyester and cotton, cellulosic fibers account for the third-highest proportion of the overall fiber market.

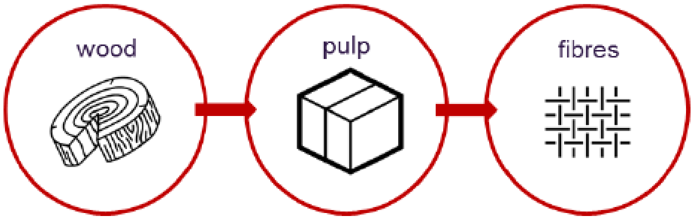

Figure 14. *Schematics of viscose fiber production (Source:https://waterfootprint.org/media/downloads/Viscose_fibres_Sustainability.pdf).*

In the viscose production process, cellulose becomes viscous with caustic soda and carbon disulfide. This method turns cellulose into a honey-colored viscous liquid. The mixture is squeezed through fine holes in the spinnerette to make long yarn filaments. The viscose yarn filaments are put into a sulfuric acid bath to harden them (Figure 14).

4.1.2 Bio-based binder

Biopolymers are natural compounds composed of monomeric units covalently bonded together. Other bio-binders' melt flow indices, impact properties, hardness, and vapor transmission are different. The engineering properties of bio-binders vary with chemistry and processing.

4.1.2.1 Starch-based binder

Starches are carbohydrates contained in plants, in particular polysaccharides having the general formula $(C6H12O5)_n$. The starches are very different in size and configuration: the smallest are rice (3–7 μm), corn is 15–20 μm, and wheat are 20–30 μm. Starches are used as filler to obtain plastics with controlled biodegradability.

Heating starch and sugar thicken and adhere to each other after. A bio-based glue is prepared based on corn starch and corn syrup. Ingredients of the starch-based glue are made of all-natural ingredients such as Mais starch, corn syrup, vinegar, and water. The production process includes boiling corn syrup, vinegar, and water together and adding this blend to corn starch and cold water. The final adhesive is obtained after hardening of boiling the final mixture.

4.1.2.2 Casein-based binder

Casein binder is a durable animal-based adhesive made from milk protein. The adhesive is known to be extremely strong over an extended length of time and to be water-resistant. Producing casein glue is virtually equivalent to making cheese by combining milk powder with vinegar, baking soda, and water. It is low energy, non-toxic, and long-lasting material.

Casein glue can be obtained easily from the milk. Vinegar separates the milk into the curds (casein), then the casein is neutralized by baking soda and mixed with water. Casein is a milk protein that repels water molecules, indicating that it is hydrophobic. In addition, casein molecules have a tendency to resist one other. Thus they float in the milk. Vinegar causes the milk to curdle. Curdled lumps are essentially casein or natural plastic, and they are pretty simple to filter out. With the addition of water and a base, the casein molecules may be separated once again. This is why it is simple to obtain the casein-based glue.

4.2 Methods

The methodology of the material tests included a series of experiments to produce a textile-based composite with silk, cotton, and viscose waste as fiber by combining different bio-based binders, which is called fiber (matrix)-binder. Firstly, textile fibers (i.e., silk, cotton, and viscose) and bio-based glues (i.e., starch-based and casein-based binder) were mixed to achieve the correct proportion for the material consistency. However, the casein-based glue failed to achieve coherency, while starch-based glue achieved it. The successful blends were molded in particular shapes to produce new samples. Secondly, the scale-up capacity of the samples was tested, preparing the 1:2 scale prototypes for each fiber to understand the application to the actual cases.

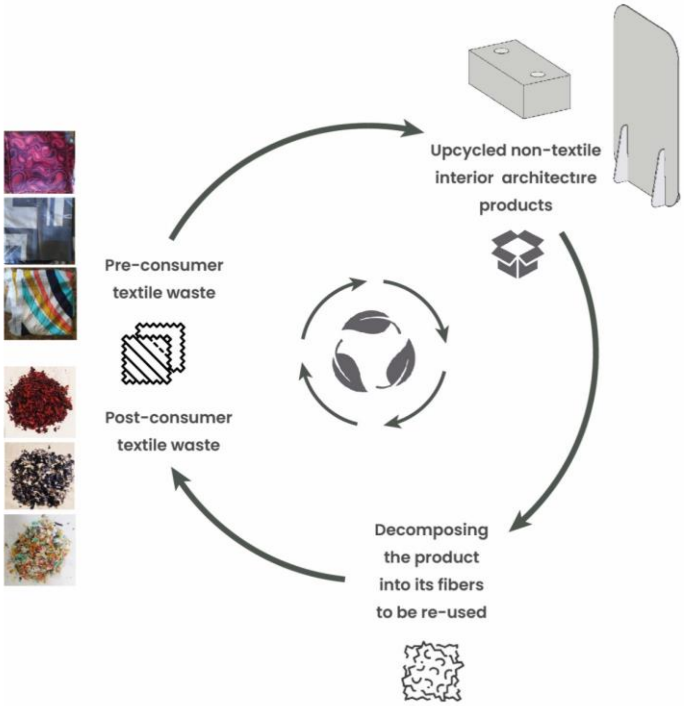

Figure 15. *Proposed architectural component production cycle with textile waste-based-materials (Drawn by the author)*

Moreover, production methods of the various interior architectural elements were explored to design textile waste products in diverse forms by combining them with different materials (Figure 15). Round wooden profiles were used as frames for intermediate-scale models to seek the possible connection details of textile-waste-based elements. Secondly, the circular textile-waste-based samples (diameter: ⌀10 cm) were prepared for the acoustic performance tests in the PSVL (Polimi Sound and Vibration Laboratory) in Politecnico di Milan. The tests and results section comparatively evaluated the acoustic performances and mechanical properties of the silk-based, cotton-based, and viscose-based materials. Finally, it is demonstrated that the various possibilities of textile waste use as an innovative, sustainable, and greenways to be used in the construction sector for the future.

4.3 Experiments for Samples and Prototypes

This section highlights the preparation of the material composites of silk, cotton, and viscose fibers with the starch-based binder. Later, the prototyping and upscaling of the textile-waste-based composites are illustrated to explore innovative ways of using upcycled materials in real office interior applications.

4.3.1 Preparation

The test materials were prepared using 100% silk, cotton, and viscose, initially available in the form of cut fabrics. Few simple types of equipment such as scissors, sieve, pan, and molds in different sizes and shapes were prepared to be used during the physical experiments. Fabric scraps are cut into small pieces in two different dimensions, approximately 4-6 mm and 15-20 mm (Figure 16). In the first phase, each three diverse textile fibers, silk, cotton, and viscose, were used as base matrix, each two diverse bio-based types of glue, starch-based and casein-based binder, were prepared (Figure 17). Before blending, both adhesives were diluted with water, and they were uniformly mixed by hand (Figure 18). The casein-based adhesive was unable to achieve consistency with the fibers; in contrast, the starch-based adhesive successfully binds each fiber to create a coherent and consistent material composition. Every three consistent blends, mixed with three fibers and starch-based glue, were used for the next steps of the experiments. The wet mixtures contained around 0,2 m^2 fibers from textile wastes and almost 60 g of glue with 20 g water.

Figure 16. *Fabric scraps fibers (a) silk waste (b) cotton waste (c) viscose waste*

The second phase involved casting the fibrous blending in a square mold to produce material samples. The excessive liquid was squeezed out utilizing a sieve, mainly to avoid an excessive binder that, if once solidified, may jeopardize the final specimen's homogenous distribution of porosity. The final mixture is then compressed in the metal molds to generate square samples in the third phase (Figure 19). Finally, the samples were put in an oven at 100 °C for 1 hour to reach final stabilization (Figure 20). 100 °C as the operating temperature to dry the samples was determined (Rubino, 2021).

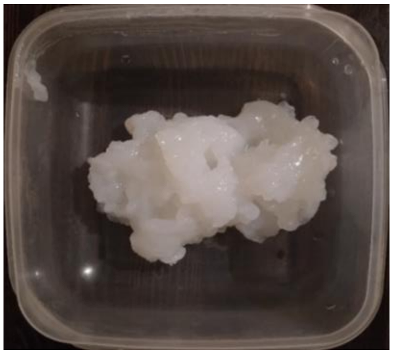

Figure 17. *Bio-based binders (a) starch-based glue*

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Figure 18. *Fibrous blend (a) silk and starch-based glue mixture (b) cotton and starch-based glue mixture (c) viscose and starch-based glue mixture*

Figure 19. *Fibrous blend in the square (80x80 mm) mold (a) silk-based blend (b) cotton-based blend (c) viscose-based blend.*

Figure 20. *Dry material samples.*

4.3.2 Prototyping and upscaling

The next step of the experiment is increasing the scale of the samples for each fiber mixed with the starch-based binder and defining the different ways to use textile-waste-based composites for interior architecture. They were decided to be used in brick and panel forms, allowing the creation of different configurations. Accordingly, the prototypes were produced on a 1:2 scale for the real applications of textile-waste bricks and panels according to the defined dimensions for better practical use.

Two silk-based bricks prototypes were prepared on a 1:2 scale in the prototyping process. Firstly, the inside of the mold was covered by the oven paper to avoid the composite sticking to the surface. The lines were drawn to sign the division of two bricks and the holes for connection details. 220 g of small-sized fibers were mixed with a 250 g starch-based binder and 250 g water mixture. The wet blend having lesser volume than the dry ones were divided in two and were put equally in the square mold (150*150*75 mm) by providing the holes with the round-shaped timber sticks. After the surfaces were flattened, the wet mixture was placed in the oven, the temperature operated as 100 °C. After several hours, the dry composite was taken from the oven and removed from the mold and oven paper. As shown in Figure 21, the production process of the silk-based bricks was completed and applied with the timber sticks, and results can be seen in Figure 22.

Secondly, the same process was implemented for the cotton-based wallcovering as paneling. The square mold was used to prepare the 150*150*20 mm cotton-based panel in scale 1:2, as shown in Figure 23.

Figure 21. *Production process of the silk-based bricks in Scale 1:2 (a) small-sized (4-6 mm) silk fibers (b) mixing the fibers with the starch-based binder (c) wet fiber-binder mixture (d) Square mold and the timber sticks for the holes (e) drying the silk-based bricks (f) removing them from the molds*

Figure 22. *Silk-based bricks (75*150*50 mm) and the load-bearing system with the timber sticks*

Figure 23. *From fibers to the composite (a) small-sized (4-6 mm) cotton fibers (b) wet binder-fiber mixture in the square mold (c) cotton-based wall covering (150*150 mm)*

4.4 Tests and Results

Nine samples, three series of three different textile fibers with the starch-based binder, besides the five samples for the acoustic tests were produced to compare them. The first series refers to the long strand fibers, the second series refers to the middle-sized fibers (15-20 mm), and the third series refers to the small-sized fibers (4-6 m). Firstly, the mechanical properties of the fourteen samples were compared. The density of each composition, fiber to binder ratio, besides the weight and volume change, were analyzed with a table. Secondly, the sound absorption coefficient tests and results were explained by diagrams.

4.4.1 Assessment of mechanical properties

Every sample is hardened, relatively durable, and has a hard surface and resistance (Figure 20, 26, 27); physical and mechanical features differ. The surface characteristics depend on the sizes and forms. The composites made of long strands have rough surfaces and are hard to shape, whereas the tinier pieces of fibers, the more plain surface the samples have and are easy to form.

The density of each fourteen samples was calculated by measuring the weight and volume. Table 4 analyzes the density based on the fiber's type and size. Density values are expressed as the mean of three measurements, with the standard deviation indicating the inaccuracy in the measuring process. Table 5 establishes the average density for silk, cotton, and viscose-based composite according to the density values for each fiber's sample in Table 4. The table shows that silk-based composites are the lightest (≈0.33 g/cm^3) and have the least volume among all samples, while cotton-based composites are the opposite as having the higher density (≈0.44 g/cm^3) and the bigger volume, and the viscose-based have the density in between both (≈0.42 g/cm^3).

***Table 4**. Physical properties of the fourteen textile-based samples with different size fibers*[9]

Sample ID	Material	Fiber sizes	Density (g/cm^3)	Weight (g)	Volume (cm^3)	Thickness (cm)
SC-1	Silk	Long strands (Width: 5-10 mm)	0,33	14	42,3	0,7
CC-1	Cotton	Long strands (Width: 5-10 mm)	0,41	21,5	53	0,85
VC-1	Viscose	Long strands (Width: 5-10 mm)	0,42	21,5	51	0,75
SC-2	Silk	Small-sized fibers (Width: 4-6 mm)	0,36	13,5	37,9	0,60
CC-2	Cotton	Small-sized fibers (Width: 4-6 mm)	0,47	25,5	54,7	0,9
VC-2	Viscose	Small-sized fibers (Width: 4-6 mm)	0,46	21,5	46,4	0,8
SC-3	Silk	Middle-sized fibers (Width: 15-20 mm)	0,31	37,5	120,4	1,7
CC-3	Cotton	Middle-sized fibers (Width: 15-20 mm)	0,43	38,9	90,5	1,45
VC-3	Viscose	Middle-sized fibers (Width: 15-20 mm)	0,37	31,5	86,5	1,35
SC-4	Silk	Small-sized fibers (Width: 4-6 mm)	0,26	15	57,8	0,8
CC-4	Cotton	Small-sized fibers (Width: 4-6 mm)	0,33	39,4	117,7	1,5
VC-4	Viscose	Small-sized fibers (Width: 4-6 mm)	0,34	23,5	68,9	1
SC-5	Silk	Middle-sized fibers (Width: 15-20 mm)	0,32	35	107,5	1,45
VC-5	Viscose	Middle-sized fibers (Width: 15-20 mm)	0,31	30	97,6	1,35

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[9] *The acoustic test samples are defined by no. 4 and no. 5 which are explained in the next section.*

***Table 5**. The average density of each textile-waste based composite*

Material	Average density (g/cm^3)
Silk-based composite	0,33
Cotton-based composite	0,44
Viscose-based composite	0,42

***Table 6**. Sample ID, density, binder/fibrous matrix percentage (in wet and dry mass), lost weight of the sample*[10]

Sample ID	Density (g/cm^3)	Fibrous matrix (Wet %)	Binder (Wet %)	Fibrous matrix (Dry %)	Binder (Dry %)	Lost weight (Dry to wet %)
SC-1	0,33	25	75	85	15	70,5
CC-1	0,41	20	80	75	25	73,5
VC-1	0,42	20	80	75	25	73,5
SC-2	0,36	20	80	90	10	78
CC-2	0,47	20	80	70	30	71,5
VC-3	0,46	20	80	70	30	71,5
SC-3	0,31	15	85	85	15	82,5
CC-3	0,43	20	80	70	30	71,5
VC-3	0,37	15	85	70	30	78,5
SC-4	0,26	20	80	80	20	75
CC-4	0,33	15	85	60	40	75
VC-4	0,34	20	80	75	25	73,5
SC-5	0,32	15	85	80	20	81
VC-5	0,31	20	80	70	30	71,5

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[10] *The acoustic test samples are defined by no. 4 and no. 5 which are explained in the next section.*

Table 6 indicates sample ID, density, binder/fibrous matrix percentage (in wet and dry mass), lost weight of the samples are illustrated. The absorption capacity of the binder for each fiber changed slightly, from 10% to 20%; however, the highest amount of lost weight of the binder in percentage is silk. The final silk-based compositions tend to have a minor binder content, around 10, 15, and 20, making it the lightest composite, while the cotton-based and viscose-based composites include a higher binder concentration, around 25, 30, and 40. The density of both composites is approximately equal. In other words, the percentage of the fiber in silk-based composites changes around 60 and 70, cotton-based and viscose-based composites around 50 and 60.

Table 7*. Physical properties of the four textile-based prototypes*

Sample ID	Material	Fiber sizes	Density (g/cm³)	Weight (g)	Volume (cm³)	Thickness (cm)	Form
SB-1	Silk	Small-sized fibers (Width: 4-6 mm)	0,29	130	450	4	Brick
SB-2	Silk	Small-sized fibers (Width: 4-6 mm)	0,28	140	506,3	4,5	Brick
CP-1	Cotton	Small-sized fibers (Width: 4-6 mm)	0,37	170	450	2	Panel
CP-2	Cotton	Small-sized fibers (Width: 4-6 mm)	0,39	90	232	1	Panel

According to Table 7, the results can be assessed more reliable finally. The silk-based bricks have the lightest density, which was the reason for selecting to produce as a brick. Cotton-based panels have the highest density, quite similar to viscose-based ones. They were chosen to be produced as sound-absorbent panels, which the reasons will be explained in the next section.

4.4.2 Acoustic performance

The five circular textile-waste-based samples (diameter: ⌀10 cm) were prepared for acoustic performance tests in Politecnico di Milano's PSVL (Polimi Sound and Vibration Laboratory) with the collaboration of Andrea Giglio.

Test setup

The normal incidence sound absorption coefficients α_n were measured by three microphones impedance tubes. In the impedance tube configuration, each test sample with a diameter of 10 cm is attached to the end of the impedance tube (Figure 24 (a)). The piston generates the distance to measure the sound absorption property. According to EN ISO 10534-2:2001, the tests for every five samples are measured for 60 seconds for both minimum (0 cm) and maximum air gap, which is calculated by the tube's length (20 cm) minus the thickness of the sample. The file exported from the customized software based on MATLAB is processed, and the sound absorption coefficient to frequency diagram is exported to Grasshopper (Figure 24 (b)). With the impedance tube method, the sound absorption coefficient values of the materials can be measured in the frequency range of 50 Hz to 6.4 kHz.

The software of the test setup generates the signal defining the voice. Sound source releasing random or pseudo-random cycle creates plane waves in a tube, and pressure is monitored at two sites near the sample. This signal is then amplified and sent to the speaker as a planar progressive wave. The ratio of the three microphones' pressure measurements is the transfer function (Özdil et al., 2020). In the acoustic impedance test setup, three microphones transfer methods were used to calculate sound pressure using microphone 1 and 2, microphone 1 and 3, microphone 2 and 3. The scheme of the impedance tube test can be seen in Figure 25.

***Figure 24**. Sound absorption test area (a) The impedance tube and the software (b) Viscose-based composite sample (the diameter = ⌀10) is placed in the impedance tube*

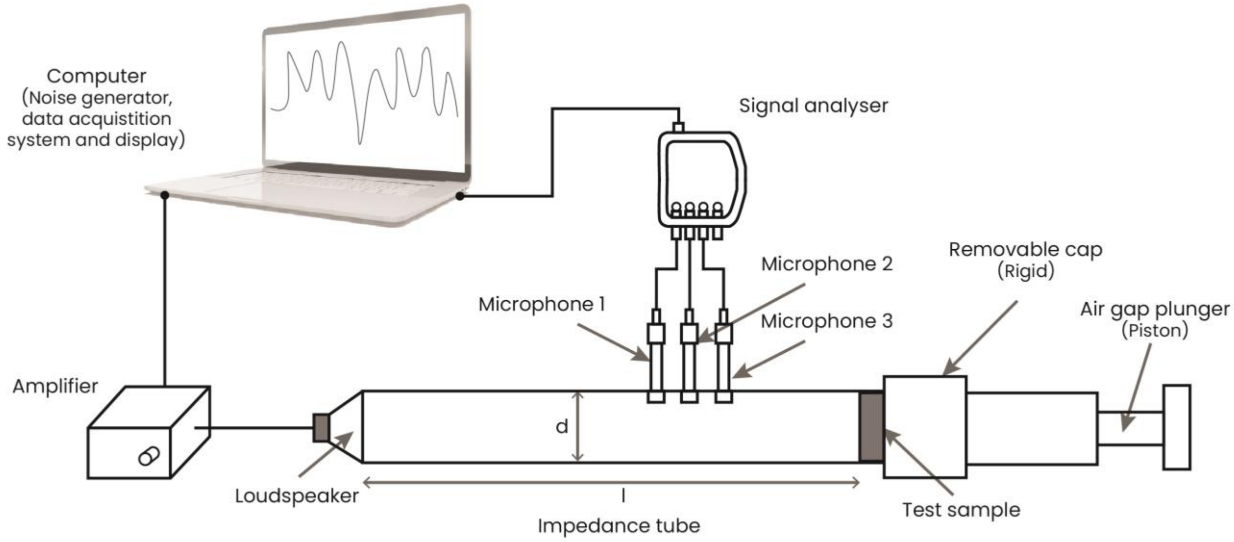

***Figure 25.** 1 Scheme of impedance tube with three microphones*

The results calculated by applying minimum (0 cm) and maximum air gap (20 cm – thickness of the sample) define the use of the sample. The minimum air gap refers to applying the sample with a layer behind it, such as wallcovering, while the maximum air gap indicates that the sample can be applied to a real case as an individual component such as screens.

The absorption coefficient is a value between 0 and 1 frequently tested across a wide range of audible frequencies to generate a performance curve for the material throughout the whole audio spectrum. Without a sample, the outcome should be 100% transmission and 0% reflection in the tube. Material samples are a barrier to the incident plane waves between the source and receiving tubes (Zhu et al., 2014). An absorption coefficient of 1 indicates that all acoustic energy impacting the surface is absorbed and none reflected. A coefficient of 0 indicates that the total energy is reflected. The second condition is almost impossible, and the first condition is unusual. The absorption coefficient differs by frequency since absorption characteristics of most materials vary at different frequencies.

In this study, three samples with small-sized fibers (4-6 mm, with the diameter ⌀10 cm), silk-based composite (SC-4), cotton-based composite (CC-4), and viscose-based composite (VC-4), besides two samples with middle-sized fibers (15-20 mm), silk-based composite (SC-5), and viscose-based composite (VC-5) were compared to each other based on their sound absorption performances. In Figures 26 and 27, the photographs of the circular samples are shown. Figure 28 and Figure 29 show the absorption coefficient diagrams and exclude the values under the reference curve. The negative values refer to the reflections from the rigid board behind the sample, which means transmitting the sound waves through the samples.

Figure 26. *Absorption coefficient test samples, each consisting of 4-6 mm length fibers and each with the diameter ⌀10 cm (the sealing tapes cover test samples) (a) SC-4: Silk-based composite sample (b) CC-4: Cotton-based composite sample (c) VC-4: Viscose-based composite sample*

Figure 27. *Sound absorption coefficient test samples, each consisting of 15-20 mm length fibers and each with the diameter ⌀10 cm (test samples are covered by the sealing tapes) (a) SC-5: Silk-based composite sample(b) VC-5: Viscose-based composite sample*

Table 8 illustrates the main physical characteristics of the samples for the silk, cotton, and viscose-based composites consisting of small-sized fibers (4-6 mm length). Figure 28 shows the absorption coefficients of those samples. The results indicate that at low frequencies between 100 and 400 Hz, VC-1 surfaces have much better sound absorption coefficient values than SC-4 and CC-4 composites. The acoustic performance of the VC-4 sample is relatively good; it can be considered an alternative to sound absorbent material in the low-frequency bandgap (for 100–200 Hz). The first peak of VC-4 appeared at 80 Hz with α rising to 0.9, and the second at 630 Hz (refers to the medium frequency), with α rising to 0.6. The VC-4 sample's absorption capacity rose in the low- and medium-frequency regions; however, it tended to show lower quality between 125 Hz to 500 Hz.

Table 8. *The physical properties of the test samples of middle-sized textile fiber composites (each consisting of 4-6 mm length fibers)*

Samples	Sample ID	Density (g/cm³)	Weight (g)	Volume (cm³)	Thickness (cm)	Surface quality
Silk	SC-4	0,26	15	57,8	0,8	Flat
Cotton	CC-4	0,33	39,4	117,7	1,5	Flat
Viscose	VC-4	0,34	23,5	68,9	1	Flat

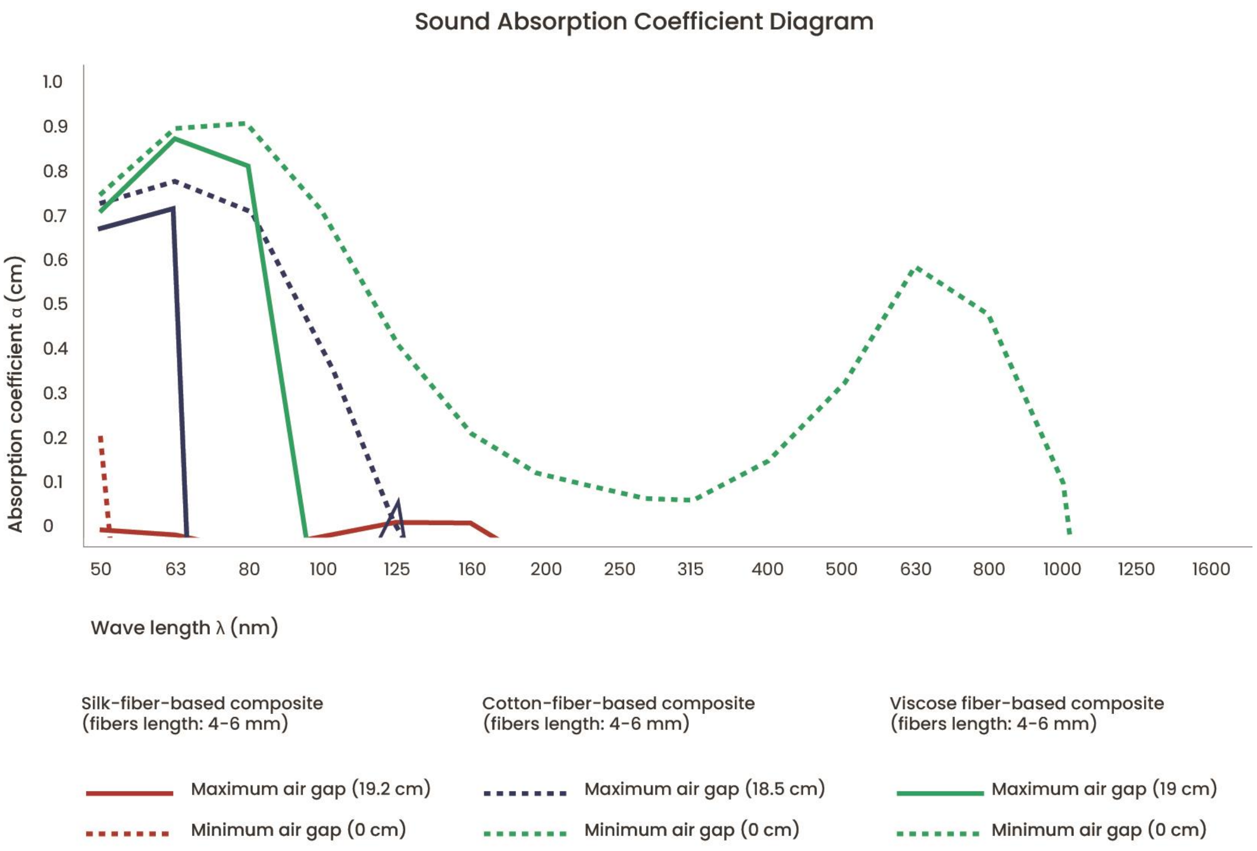

Figure 28. *Sound absorption coefficient test samples, each consisting of 4-6 mm length fibers (Extracted from the Grasshopper software by the author)*

Table 9 indicates the main physical characteristics of the samples for the silk and viscose-based composites consisting of middle-sized fibers (15-20 mm length). Figure 29 shows the absorption coefficients of those samples. The results show that the sample SC-5 and VC-5 revealed a similar acoustic behavior with moderate absorbent capability for the very low and low up to 100 Hz) frequencies with an α value equal to 0.5 in 100 Hz, referring to the human voice.

Table 9. *The physical properties of the test samples of middle-sized textile fiber composites (each consisting of 15-20 mm length fibers)*

Samples	Sample ID	Density (g/cm³)	Weight (g)	Volume (cm³)	Thickness (cm)	Surface quality
Silk	SC-5	0,33	40	120,4	1,45	Rough
Viscose	VC-5	0,31	30	97,6	1,35	Rough

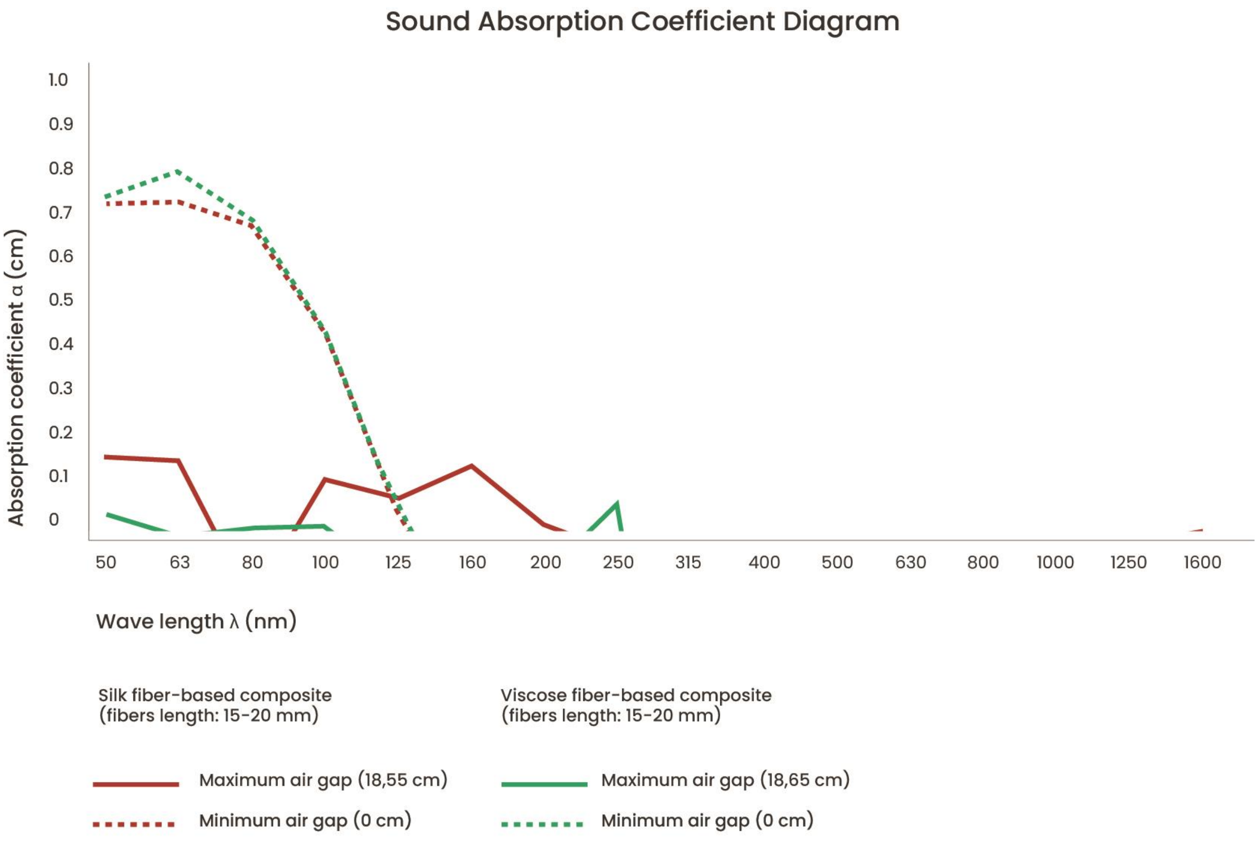

Figure 29. *Sound absorption coefficient test samples, each consisting of 15-20 mm length fibers (Extracted from the Grasshopper software by the author)*

Test findings

Most samples exhibited poor acoustic behaviors due to the low thickness of the sound waves transmitted through the samples. Only the VC-4 sample exhibited relatively good sound-absorbing performance for low frequencies (α = ≈0.9 in 80 Hz) and medium frequencies (α = ≈0.6 in 630 Hz), which can be competitive. CC-4, SC-5, and VC-5 samples showed a moderate performance (α = ≈0.5 in 100 Hz) in very low frequencies referring to the human voices. When the minimum air gap is applied in the tube, VC-4 has the best potential for wallcovering, besides CC-4, VC-5, and SC-5 have low capacity. However, when maximum air gap was applied to the tube, only VC-4 and CC-4 have lower but promising performances as individual sound-absorbent components. However, it is possible to enhance the acoustic performances of the samples.

According to Islam & Bhat (2019), high-density textile fibers can significantly increase sound absorption in the mid-to high-frequency range. Thicker materials have a lower air permeability but better absorb sound waves. Reducing the binder percentage to 10%-20%, a porous and flexible structure might be achieved, resulting in decreased heat conductivity and increased sound absorption capacity (Rubino, 2021). Moreover, upcycling textile fibers into non-textile products by combining them with a bio-based binder can be used as sound-absorbing materials. However, the current samples need to be considered in terms of increasing thickness to avoid transmitting the sound waves through the material, porosity between fibers, softer surfaces, higher fiber density, and lower binder concentration for better acoustic performance.

5 DESIGN IMPLEMENTATIONS

Through a growing interest in sustainability, future interiors may incorporate new technology and better approaches to reduce energy consumption and carbon emissions. High-energy-embodied materials such as cement, glass, brick, and steel can replace less-energy-intensive hollow concrete, rammed earth, wood, recycled materials made of fiber waste such as textile, and agricultural waste such as fly ash and bamboo leaves for a better and healthier interior environment. The environmental impacts of interior construction and finishing materials consisting of natural materials (i.e., stone, wood), converted materials (i.e., tiles, bricks), and artificial materials (i.e., plastic, pigments, and glass) (Alfuraty, 2020) can be seen comparatively in Figure 30. For example, the EIA (Energy Information Administration) highlighted that cement was identified as the most energy-intensive manufacturing industry in 2013, and it caused the cement to reduce reliance. Thus, home and office interiors can house more natural and recycled materials than the cold, detached greys of today's steel, concrete, and glass in the future (Cao, 2020).

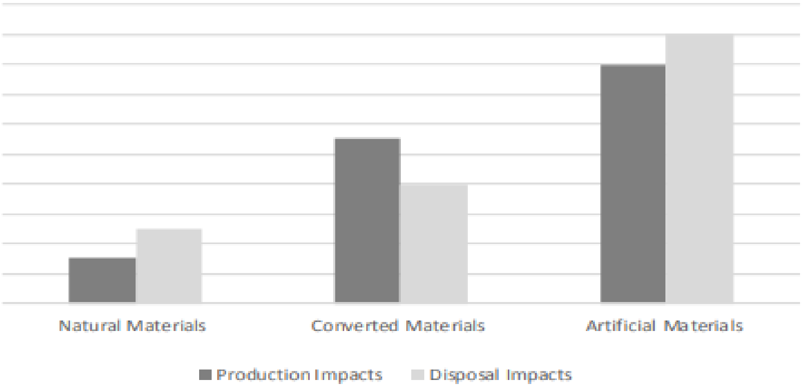

Figure 30. *The impacts of the materials on the environment (Alfuraty, 2020)*

Moreover, recent research has shown that interior items' cumulative embodied carbon impact is underestimated. WRNS Studio, an architectural and urban company, calculated the embodied carbon footprint of the Janet Durgin Guild & Commons for Sonoma Academy; and interior finishes accounted for almost 7% of the total. CLF and LMN Architects of Seattle found that interior designers are responsible for carbon emissions equal to the footprint of the building’s structure and envelope with the renovations due to the changes in the organizational demands (Rajagopal, 2020). Furthermore, the Carbon Leadership Forum conducted a groundbreaking analysis on improvement initiatives in five different workplaces and found that cubicles, acoustic panels, ceiling panels, and flooring all had substantial carbon footprints (Figure 31).

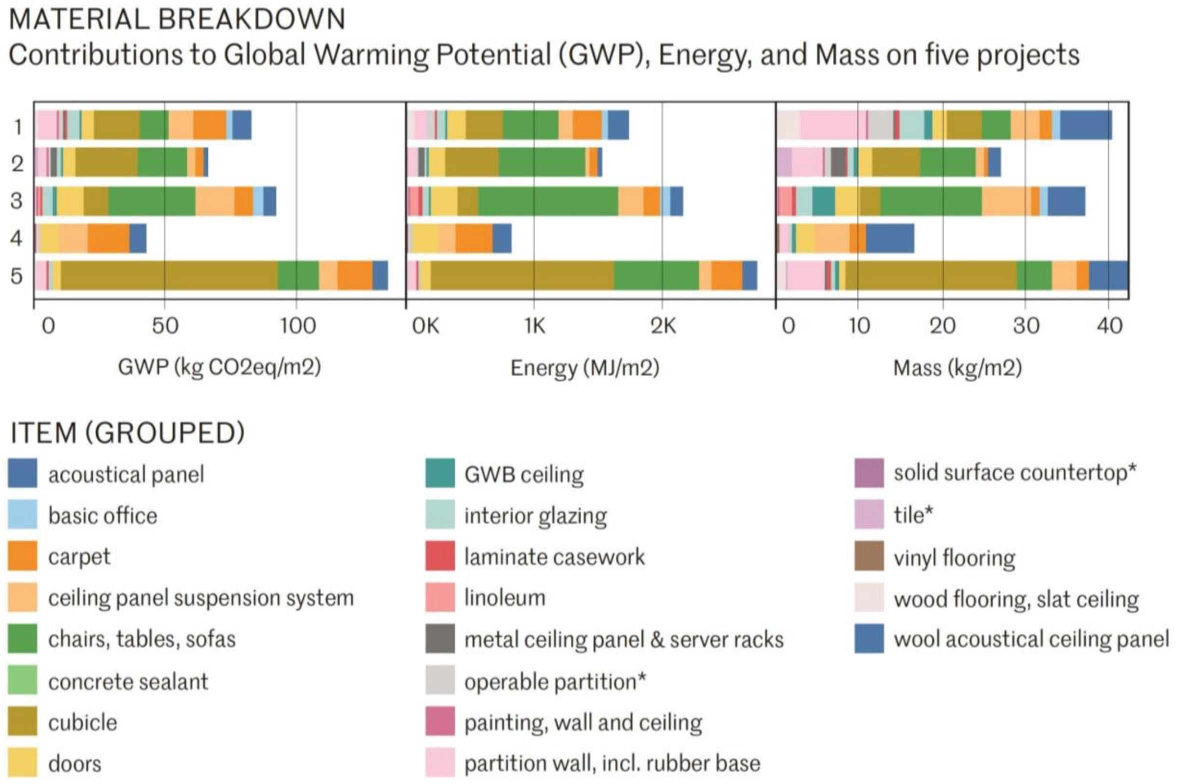

***Figure 31**. A material breakdown showing contributions to "Global Warming Potential (GWP)," Energy, and Mass on five projects* (Rajagopal, 2020).

5.1 Methods and Objectives

An office interior design project is proposed to finalize the literature study and experimental part and eventually apply the proposed materials in the actual case study, Palazzo del Capitano di Giustizia.

The headquarters of the Central Command of the Milan Local Police building has a traditional office layout, and it is obligatory to adjust the organization according to the needs of today. The layout of contemporary office buildings offers an opportunity to explore the different uses of textile waste in the interior with a better acoustic performance which is well-known for influencing human well-being—instead of poor acoustics, small rooms with too many divisions, organizing open office areas as large rooms to work, have meetings and rest.

Separations of the large rooms are created as lightweight, temporary, and mobile instead of heavy, permanent, and strict divisions. Hence, textile-waste-based applications can be applied as screens to divide and define the working areas, desk dividers and implemented as wall covering in the meeting rooms to improve the acoustic comfort with sound-absorbing quality.

Consequently, the proposed materials made of textile leftovers can enhance the quality of the office interior with sound-absorbing treatment and contribute to the ecological health of the environment by promoting the use of waste materials.

5.2 Selection of the Building Site

The incentive of the sustainable and recycled interior building materials' use in the public buildings can be a practical starting point since they are the places accessible by the public, and people spend time there either necessarily or optionally. Starting the use of environmentally friendly materials in public buildings can also increase their use, making them visible by private organizations, companies, and individuals. Moreover, the selection of the public buildings is significant in terms of the government's role in undertaking the responsibility and encouraging the choice of ecological materials. On the other hand, office buildings offer multiple ways of using ecological materials because of their flexible design capability. In this regard, a public office building, The Palazzo del Capitano di Giustizia, was selected as the project area.

The Palazzo del Capitano di Giustizia is a historical palace in the city of Milan, located at the Verziere between Piazza Fontana and Piazza Beccaria, today the headquarters of the Central Command of the Milan Local Police. The palace building is located in the very central area of Milan, behind the Duomo di Milano, next to the historical Piazza Fontana and Piazza Beccaria, near Galleria Vittorio Emanuele II and La Scala Theater, and housing exclusive fashion districts.

The construction of the historic building was started in 1578 and completed in 1605 by the architect Pietro Antonio Barca. The significant renovation was carried out in 1879 by the architect Agostino Nazari. After the extensive damage that occurred after the bombings in World War II, the reconstruction was completed in 1960 directed by the architect Piero Portaluppi.

5.3 Design Project: Palazzo del Capitano

The palazzo is a three-story building with a large central courtyard, the building consists of a repeated layout of the offices mainly, and the offices are distributed on the floors with an intensely rigid organization, strictly subdividing the spaces. Each staircase connects to various units and departments in an unusual articulated layout across multiple stories. The building has various coordination offices, services to citizens, and logistic areas.

The selected area from the Palazzo del Capitano building is on the Northern part of the first floor. The reason why is that the ground floor and third floor have more complex office organizations because the ground floor has an entrance hall facing the public with a central courtyard. The third-floor results from the later modifications, and some parts are dedicated to the technical area. The second floor is dedicated to the call center, which needs soundproof materials. The first floor includes general information units with a very standard layout since the proposed project aims to demonstrate the various uses of textile-waste-based materials in different architectural components.

A series of design strategies were proposed for the selected office area on the first floor in the Palazzo del Capitano building. The design solutions have been created based on user experience to increase the standards by utilizing the surveys for the workers and interviews of the managers, which were conducted by the team of the course "Thesis Workshop" (2020-2021) coordinated by Ingrid Paoletti, Maria Pilar Vettori within the collaboration of the Architecture, Engineering, and Built Environment department of the Politecnico di Milano of and Milan Municipality.

The selected area from the building "Palazzo del Capitano" is located on the north part of the first floor, and it is specialized for the general information units offices. The proposed area has been designed to adjust the new approaches for future offices with sustainable product choices by organizing the space efficiently, providing ergonomics and flexibility for the working spaces. It considers the needs and requests of the users in the building.

5.3.1 The framework of the project

The framework for the interior design project is defined following the methodologies and objectives. The Palazzo del Capitano is an excellent example of a well-preserved historic structure that contributes to the city's identity and cultural heritage. The current layout of the spaces, on the other hand, is rigid and insufficient to suit the current needs, and the existing materiality is unsustainable. All in all, it is vital to combine new materiality with an eco-friendly strategy to adapt cultural heritage to contemporary needs and improve its quality on functional, environmental, and economic levels.

Most offices in such historic buildings in Italy have a rigid layout, partitioning the space strictly. A large number of partition walls causes the interior load to be heavy-weight, and the materiality of the interior walls lack lightweight and sustainable solutions due to the segmentation of the office area. The existing traditional materials are primarily plasterboards for the division of the rooms, MDF and plastic for the furniture, steel equipment for the lockers, and heavy wood materials for the wall coverings. This interior architecture presents an old-fashioned style with an uncontemporary approach (Figures 32 and 33). Using sustainable and lightweight materials, creating an interior design promotes bio-based, bio-degradable, recyclable, and renewable products. Also, the photos of the building with its surrounding can be seen in Figure 34.

As a result of specified reasons, the architectural project for the selected area proposes a new office layout to meet the requirements and shortages by supporting the ecological point of view.

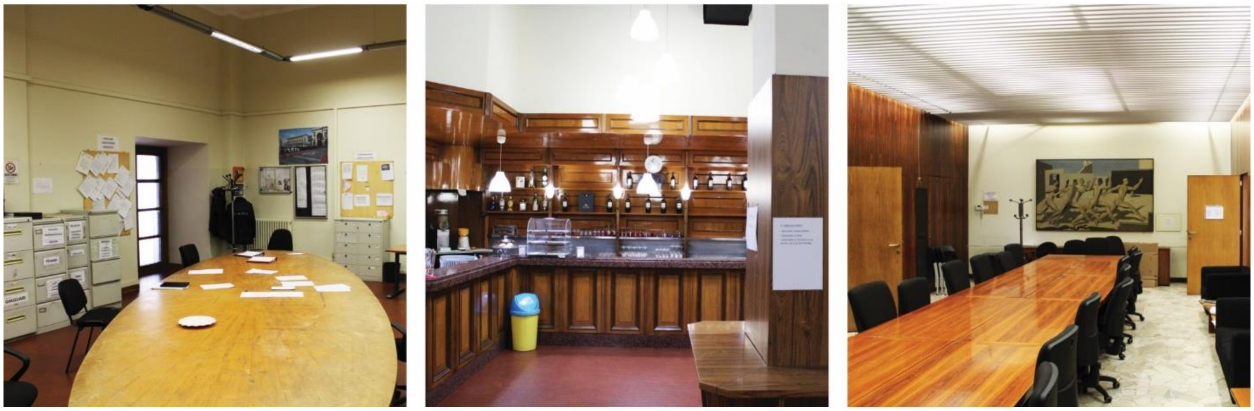

Figure 32. *Photos from the interior of the Palazzo del Capitano (a) The long corridors (b) Open office area (c) Conference room*

Figure 33. Photos from the Palazzo del Capitano interior (d) Office meeting area (e) Canteen/bar (f) Meeting room

Figure 34. *Photos from the courtyard and outside of the Palazzo del Capitano (a) the surrounding of the building in the central Milan, (b) the Palazzo del Capitano from the Piazza Cesare Beccaria (c) the main entrance of the building (d) the central courtyard of the building*

The survey completed by the operators of the building and implemented by the "Thesis Workshop" (2020-2021) course team shows that there is a strong need for better quality spaces, shared workstations, and enlargement and renovation of the resting areas in addition to the need for an increase in service areas such as changing rooms, restrooms, and bar. The building needs to organize better to avoid the current state of disorder due to the visual quality of the space. Also, the employees spend most of their time in the office area.

Thus, it is crucial to design spacious, flexible, and integrated office areas with different facilities for both working and resting.

In terms of function, the designed office area contains different workspaces with several individual offices, open offices, individual-working, co-working areas, meeting rooms, and qualified service areas. The new office layout offers more open and spacious spaces with resting areas, a kitchenette, and places for collaborative activities such as formal and informal meetings, including multimedia presentations and co-working spaces to increase functionality. According to the interviews, the operations of the various police commands vary widely, and the responses tend to emphasize office tasks involving deep reasoning activities. Besides, the department heads and the representative of the different units declared that frequent contact with other police commands or municipal bodies is significant, typically by phone or video. The building needs efficient tools and direct communication places. The specialized areas for phone and video calls are proposed to provide the need for the smart work trend increasing collaborative workplaces and decreasing fixed workstations (Anishchenko, 2021).

Moreover, office areas are noisy, and 59% of the operators indicated they need visual and acoustic privacy while working (Anishchenko, 2021). Sound-absorbing materials are preferred to allow sound to be reflected minimum and lower the reverberation of sounds caused by human interaction in the office. In addition to the upcycled materials choice with sound-absorbing treatment, the selected construction methods are based on dry construction techniques to modify, assemble, and dismantle for reconfiguration easily.

Ecologically, proposed materials for the screen walls, interior wall coverings, and furniture are upcycled bio-based and bio-degradable textile-waste-based products in various forms and sizes. On the other hand, using environmentally friendly products in the office interior can lower the risk of eco-anxiety caused by the psychological effects of climatic crisis for the people who work there and spend most of their time inside the office[8]. Designing a warm and calm space to work together with less stress is essential. It can significantly impact job satisfaction and physical and psychological health.

5.3.2 Regeneration of indoor spaces

The selected office area on the first floor (Figure 35) is regenerated, considering the needs of today. The traditional layout consists of highly long corridors and strictly divided rooms. The existing use is defined rigorously, and it prevents multi-purpose uses. As discussed in the previous chapter, considering all the drawbacks of the current use and the new requirements, a new office layout was proposed (Figure 36), offering functional, versatile, and flexible uses. The proposals contains the design of screens, panels, and furniture made of different possibilities of textile-waste composites selecting the most suitable one among silk, cotton, and viscose composites in terms of their density, and sound-absorbent capacity.

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[9] https://www.bps.org.uk/sites/bps.org.uk/files/Member%20Networks/DOP%20Going%20Green%20The%20Psychology%20of%20Sustainability%20in%20the%20Workplace.pdf

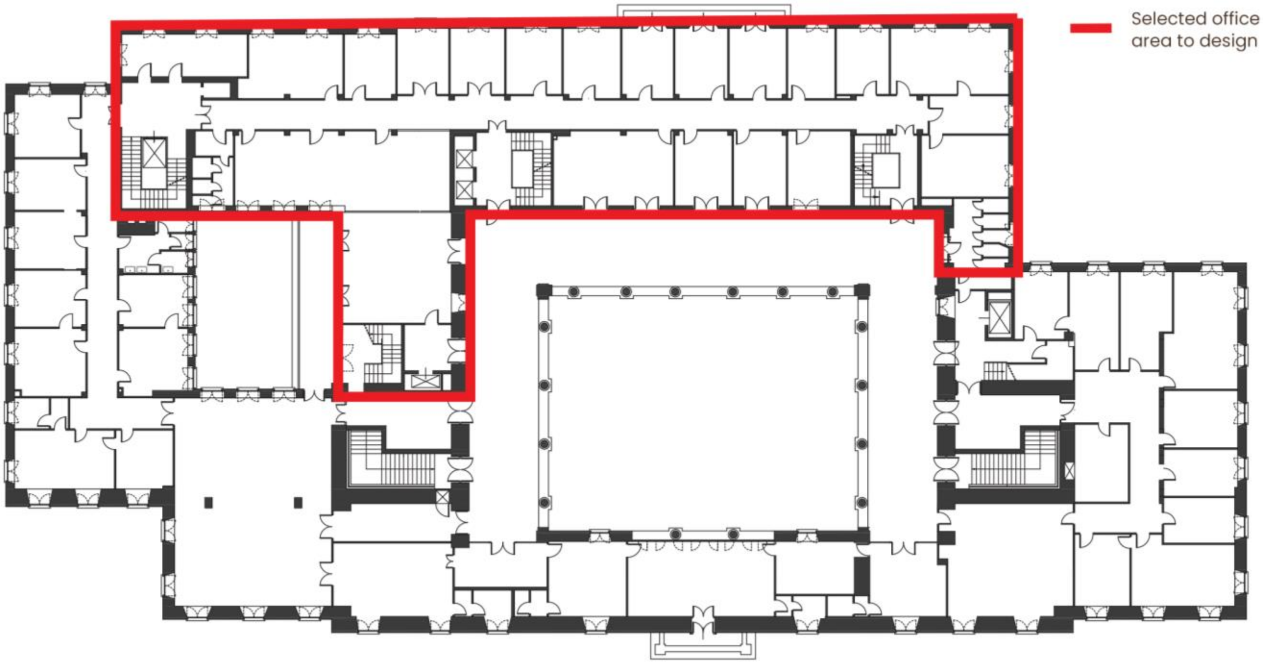


***Figure 35**. The existing first-floor plan and the selected area. Scale 1:500 (General Information Units)*

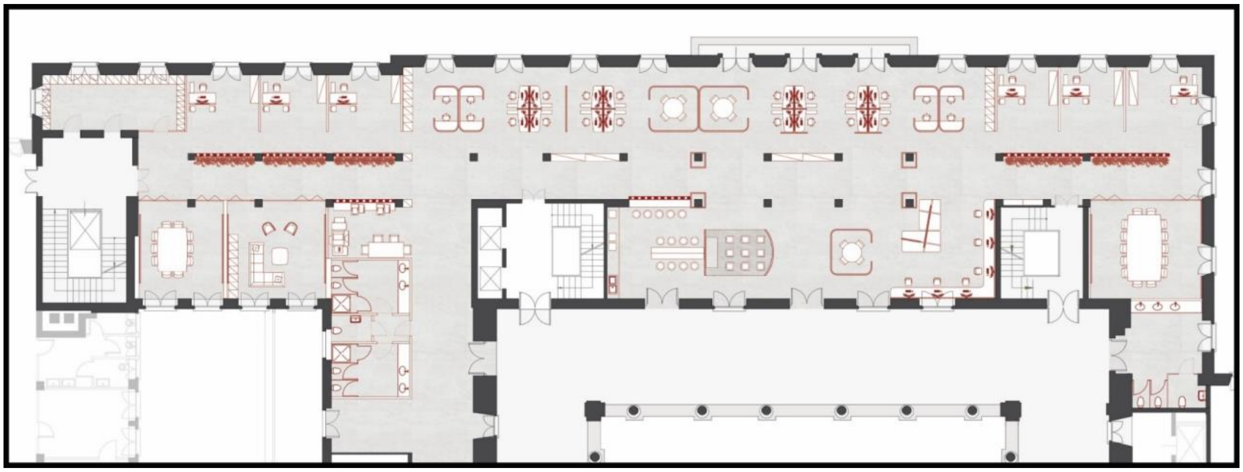


***Figure 36**. The proposed first-floor plan of the selected area (See Appendix 1). Scale 1:400 (Drawn by the author)*

The axonometric view in Figure 37 illustrates the functional analysis of the proposed office layout. Moreover, Figure 38 shows the specialized office areas in terms of function, while Figure 39 expresses the various uses of textile-waste-based composites in the office areas.

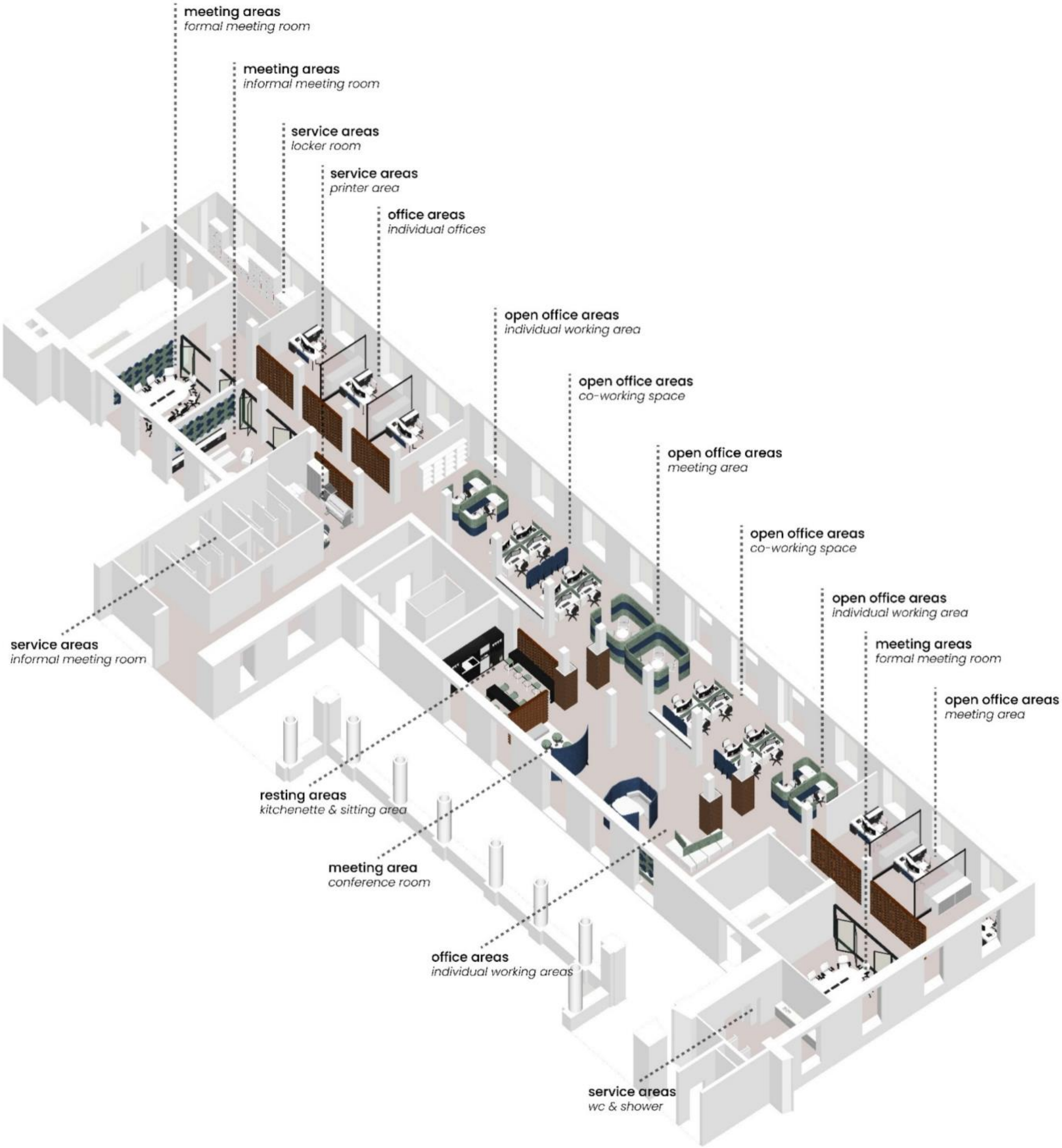


Figure 37. *Function analysis of the proposed floor plan of the selected area (See Appendix 2) (3D modeled and illustrated by the author)*

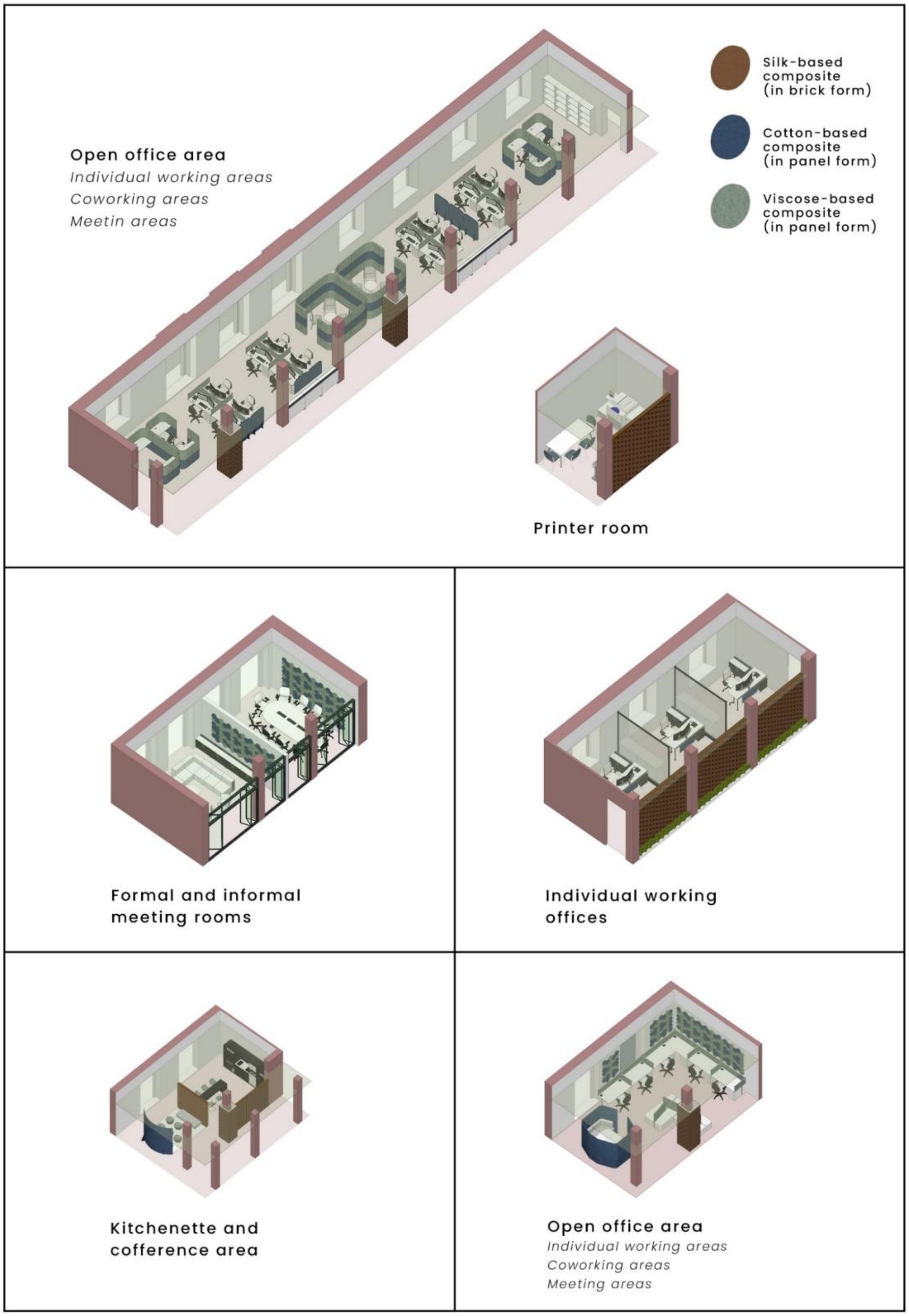
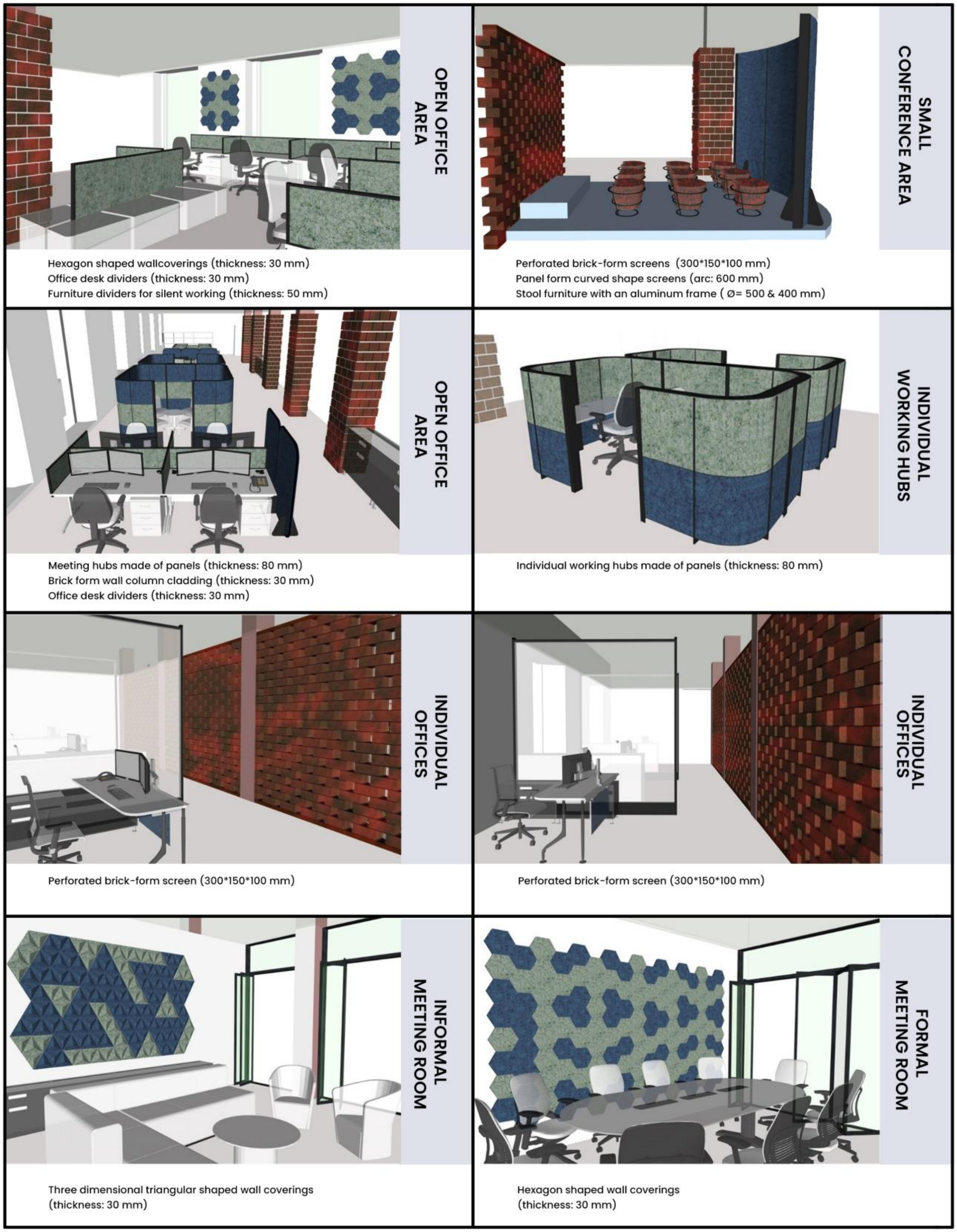


***Figure 38**. Proposed office areas specialized in terms of function (See Appendix 3) (3D modeled and illustrated by the author)*



Hexagon shaped wallcoverings (thickness: 30 mm)
Office desk dividers (thickness: 30 mm)
Furniture dividers for silent working (thickness: 50 mm)

Perforated brick-form screens (300*150*100 mm)
Panel form curved shape screens (arc: 600 mm)
Stool furniture with an aluminum frame (Ø= 500 & 400 mm)

Meeting hubs made of panels (thickness: 80 mm)
Brick form wall column cladding (thickness: 30 mm)
Office desk dividers (thickness: 30 mm)

Individual working hubs made of panels (thickness: 80 mm)

Perforated brick-form screen (300*150*100 mm)

Perforated brick-form screen (300*150*100 mm)

Three dimensional triangular shaped wall coverings
(thickness: 30 mm)

Hexagon shaped wall coverings
(thickness: 30 mm)

Figure 39. *Various textile-waste based composites use in the office interior (See Appendix 4) (3D modeled and illustrated by the author)*

5.3.2.1 Screens

A functional and safe environment, suitable places for concentration and productivity are favorable for the office workers since the employees need to focus intensely to make successful reasoning. Office screens are the best solutions to provide a practical, versatile, and convenient interior dividing the areas for operational needs, isolating the workstation and providing privacy for people. Moreover, screen walls can mitigate the dense view of numerous steel lockers to keep the documents by providing a controllable view and breaking the cold appearance of grey metal. The additional benefits of the screens are their flexibility, portability, simplicity of installation, and dismantling. They can be placed between the office desks and the gathering and transition areas such as corridors. Various color alternatives offer a warm and calm ambient for the office spaces.

Two types of screen walls are proposed for the selected office area in Palazzo del Capitano. The first one is designed as a perforated load-bearing screen wall consisting of silk-based bricks (150x300x100 mm) (Figure 40). The brick module’s material is decided as silk since it is the lightest composite. The transversely placed bricks with symmetric two holes allow the porosity to the wall. The aluminum plates in the base and top and the round aluminum profiles stabilize the brick configuration. The silk-based brick screens' height is 2,00 – 2,20 meters (Figure 41). They are proposed to define the individual office rooms and isolate them from the corridor, meeting areas, and printer room.

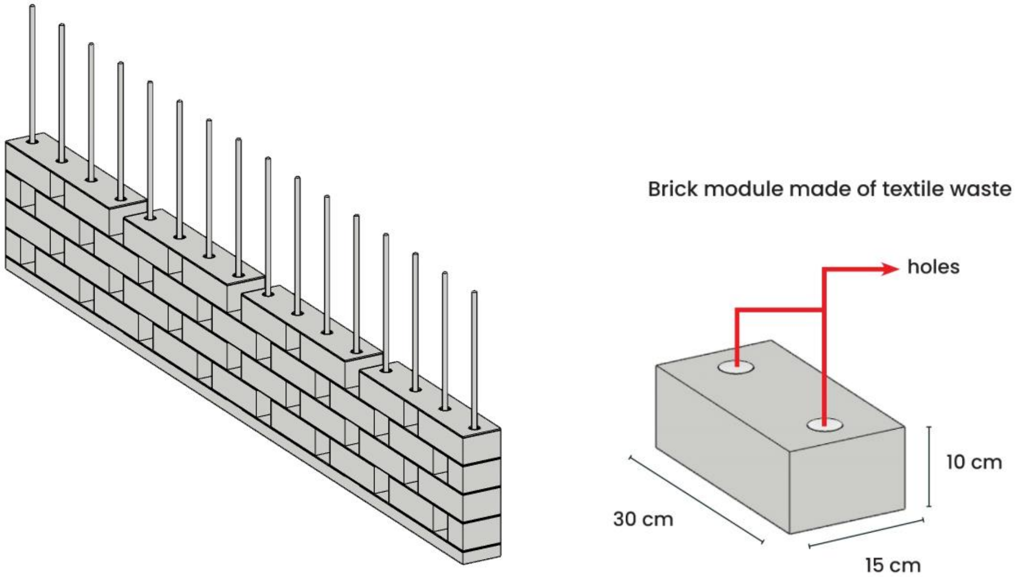


***Figure 40**. Textile waste based porous wall in brick form (Drawn by the author)*

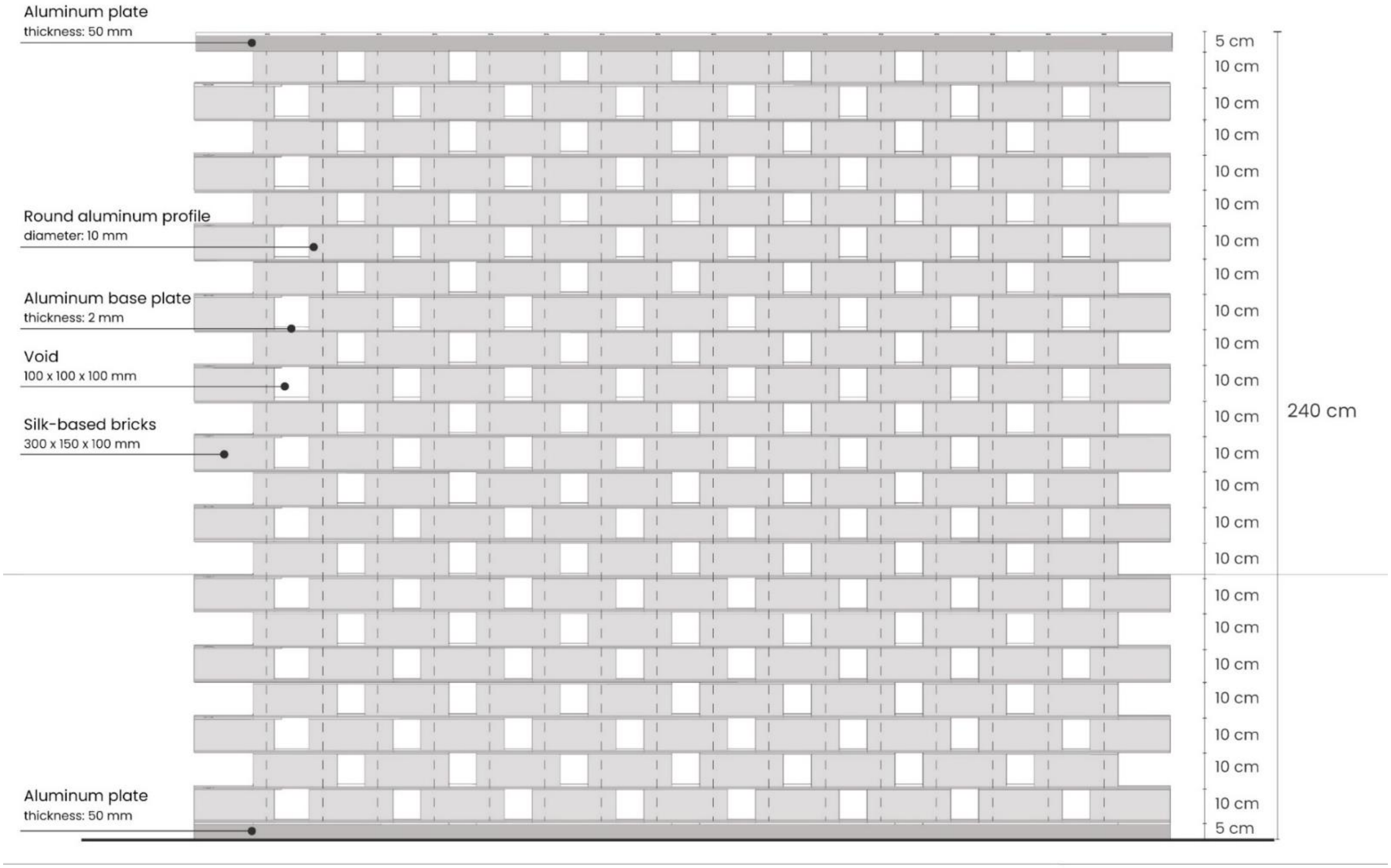


***Figure 41**. Textile waste-based porous wall in brick form (Drawn by the author) Scale 1:20*

The second one is designed as panels for defining semi-closed spaces such as meeting areas or individual working hubs, or defining some areas such as open conference hall, besides dividing the multiple workstations into open office areas to provide visual privacy and the acoustic quality of the workplaces by lowering background noise disruption. As shown in Figure 42, solid panels can function as a system component defining spaces such as meeting and individual working areas, while the curved panels can partially divide the space, as shown in Figure 43. Also, a solid panel can divide working spaces into more private areas and increase acoustic performance (Figure 44). The panels can work as either portable or stable office components. Figure 44, 45, and 46 illustrates the technical drawings of various screens proposals consisting of panels.

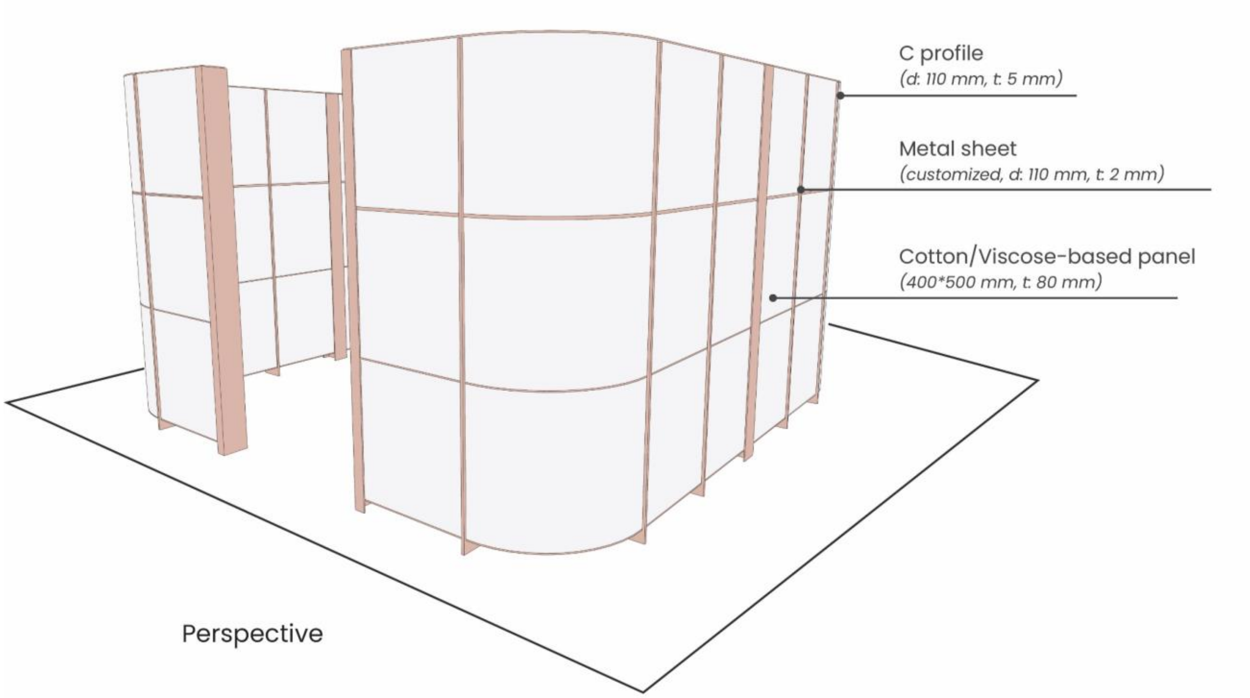


Figure 42. *Perspective view of the semi-closed area designed with textile waste-based panels supported with aluminum frames (Drawn by the author)*

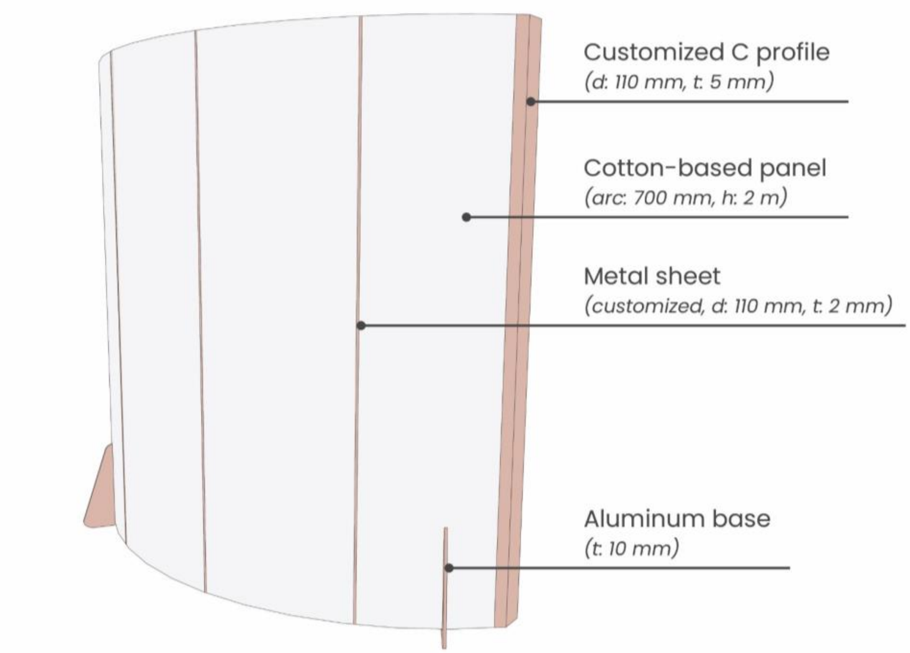


Figure 43. Perspective view of the curved panels based on textile waste supported with aluminum frames (Drawn by the author)

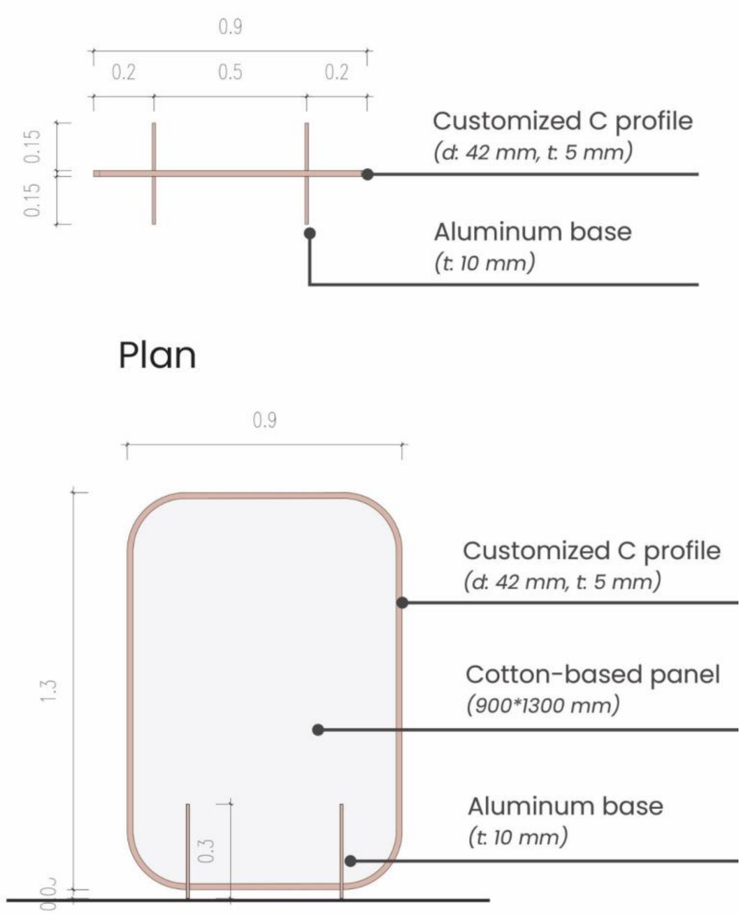
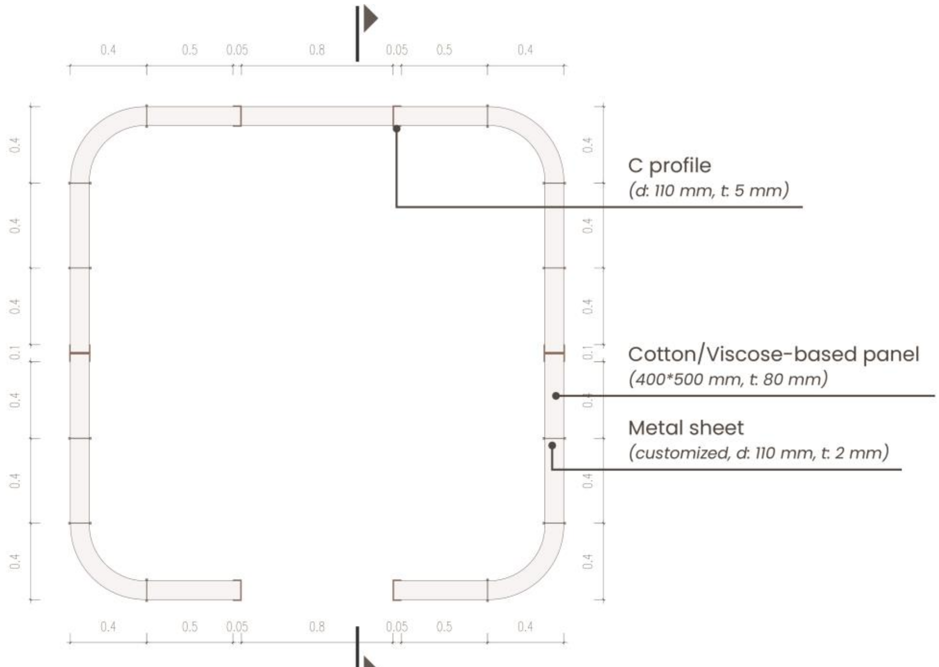
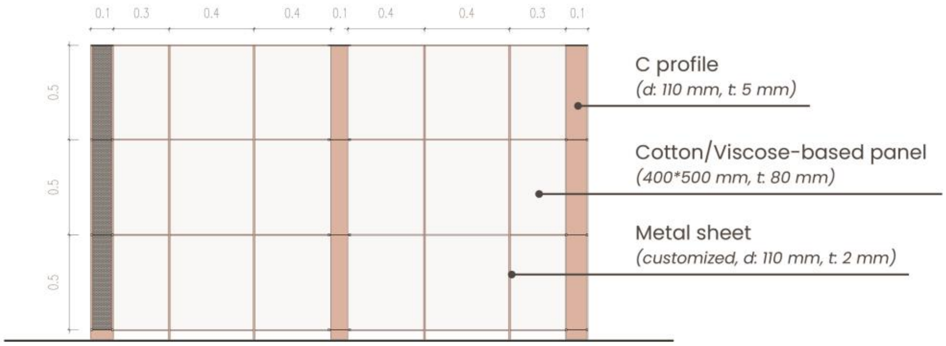


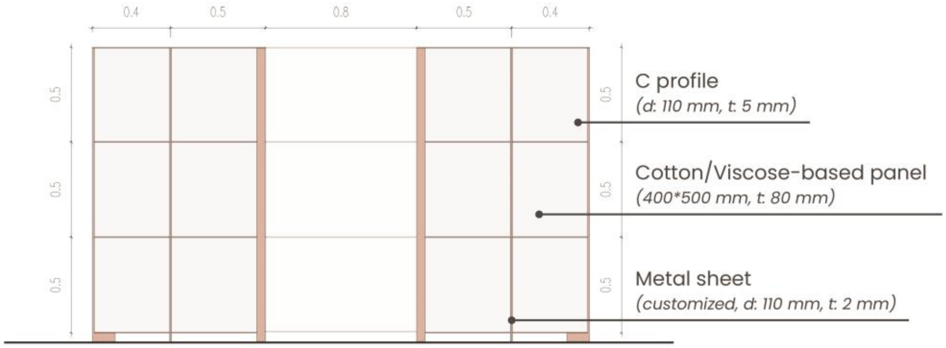
Figure 44. Plan and elevation views of the portable panel based on textile waste (Drawn by the author) Scale 1:25



Plan



Section



Elevation

Figure 45. *Plan, section, and elevation views of the semi-closed area (Drawn by the author) Scale 1:40*

In Figure 45, the screens are proposed to be made of cotton and viscose-based panels, defining the compact meeting areas and individual workstations by creating a semi-closed environment. The panels have approximate (because of rounded edges) dimensions of 500 x 500 x 80 mm. In both the vertical and horizontal directions, round aluminum profiles are used to link each panel to create a standard-sized screen, and aluminum C profiles are used to frame each screen board to design the system. Three panels are stacked vertically as a screen, and the semi-closed regions' total height is defined as 1.5 meters.

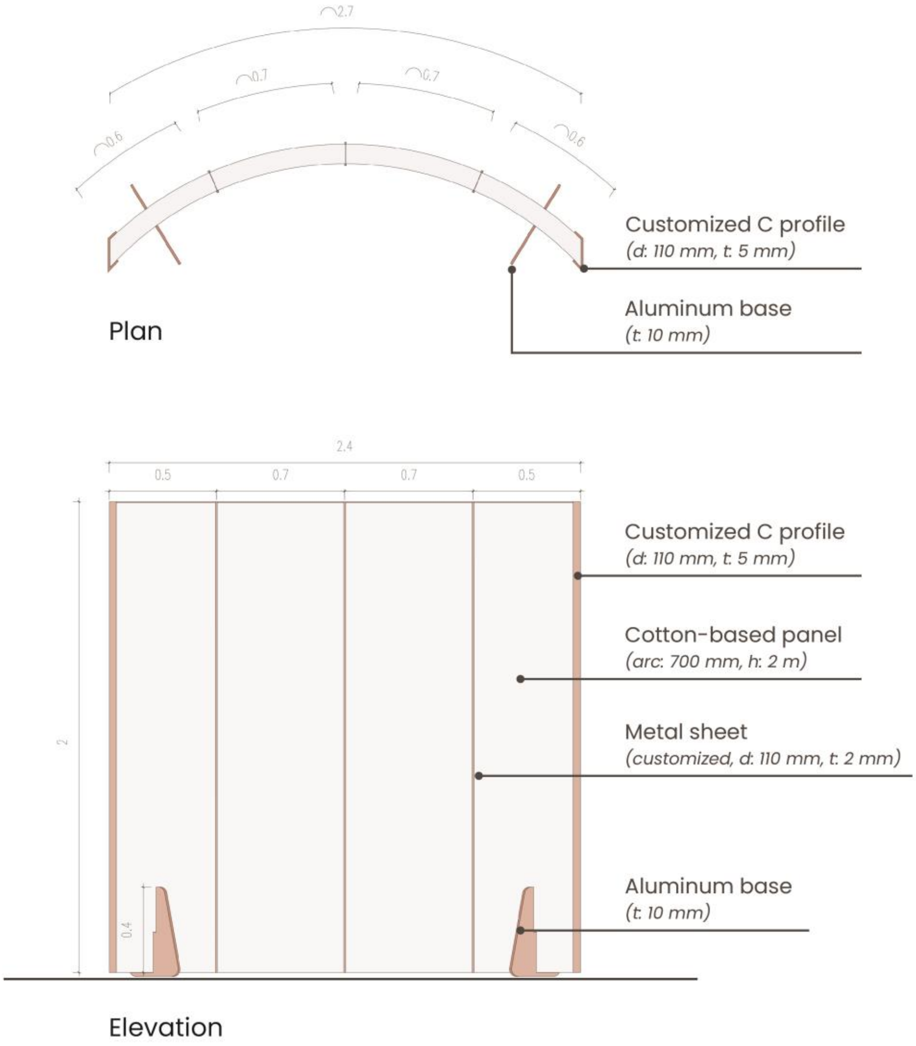


Figure 46. *Plan and elevation views of the curved panels (Drawn by the author) Scale 1:40*

5.3.2.2 Wallcovering

Wallcoverings made of cotton-based and viscose-based composites are suggested to improve the sound-absorbent performance of the meeting rooms and co-working spaces for increasing productivity and concentration. The sizes and shapes are flexible depending on the aesthetic appearance of the space, creating brick and hexagon patterns and three-dimensional triangular patterns on the wall (Figure 47). The application method is sticking the coverings to the wall. The bio-based adhesives should be preferred to stick the wall coverings.

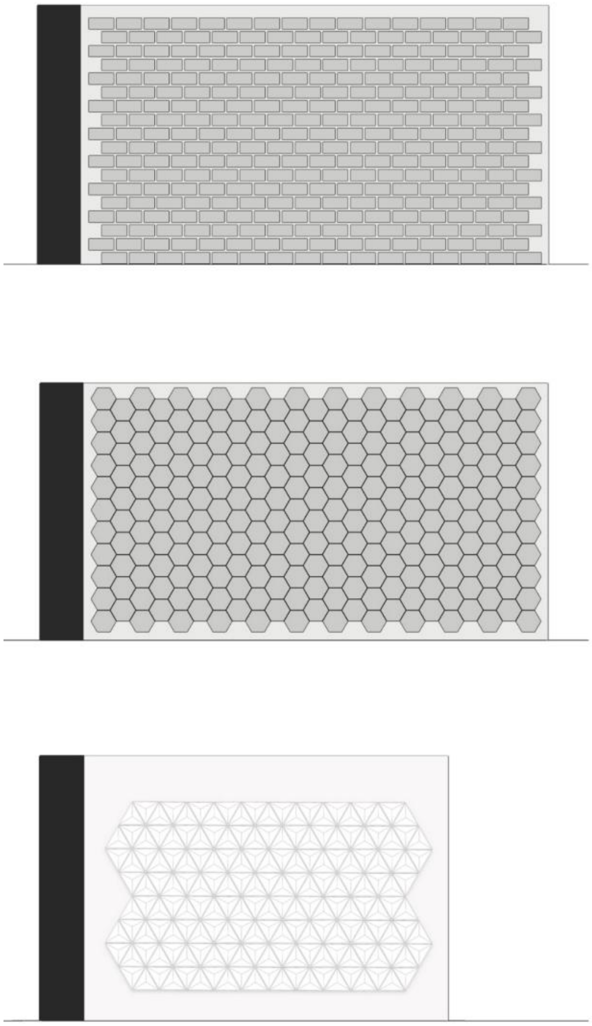
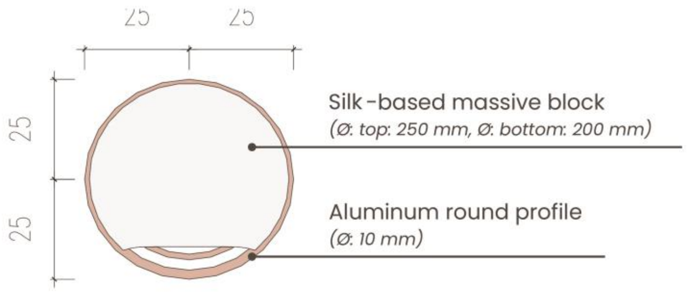


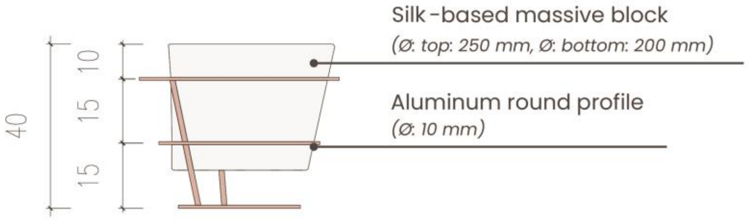
Figure 47. Brick pattern & hexagon pattern & three-dimensional triangular wall claddings (Drawn by the author)

5.3.2.3 Furniture

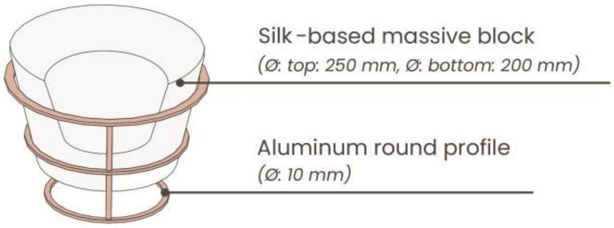
The third proposal made of textile-waste composites is the furniture such as stool, and desk dividers. The stools can be used in the small conference area and kitchenette, the desk dividers can be used in the office desks. The lightest silk-based fibers are formed in the massive blocks by using molds in particular shapes, and the blocks are placed in the aluminum frame. Secondly, viscose-based sound-absorbent desk dividers are the second possibility for the furniture proposal. The rectangular panels framed with hollow section aluminum profiles can be placed between the office desks. Technical drawings of the stool and desk dividers can be seen in Figures 48 and 49, respectively.



Plan

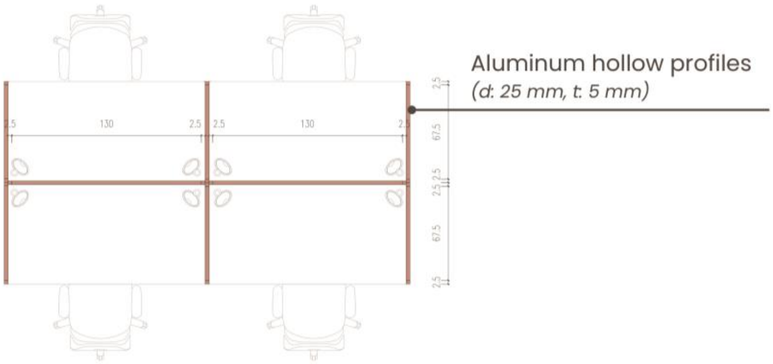


Elevation

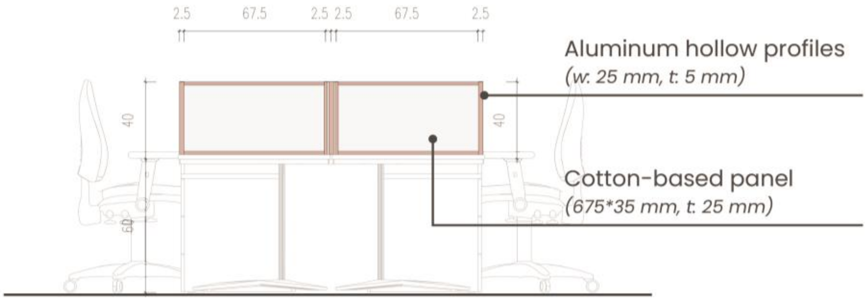


Perspective

Figure 48. *Plan, elevation and perspective views of the stool furniture made of textile-waste massive blocks and supported with an aluminum frame (Drawn by the author) Scale 1:’20*



Plan



Elevation

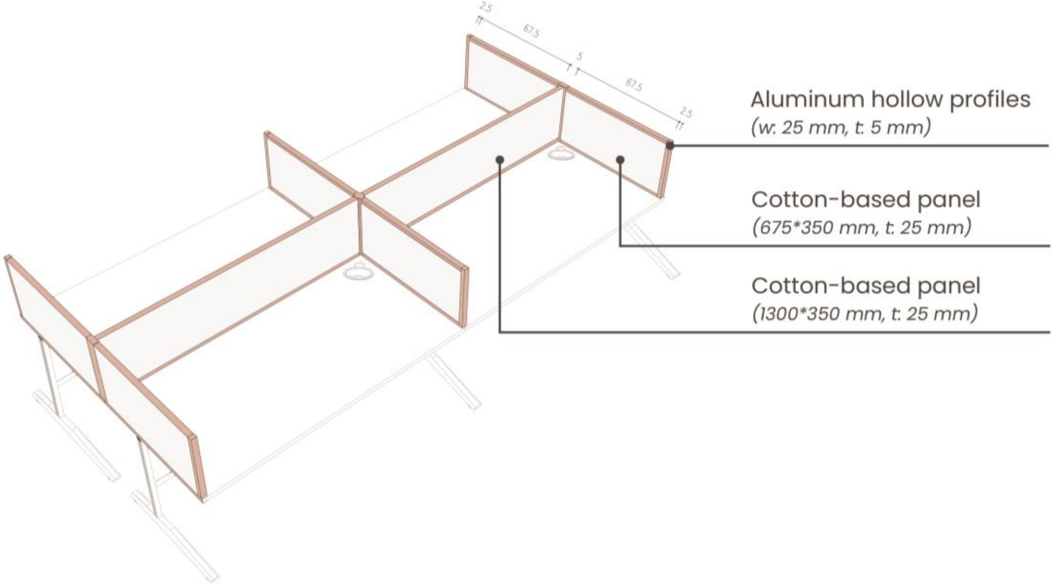


Figure 49. *Plan, elevation and perspective views of the desk dividers made of textile-waste based panels framed with an aluminum profile (Drawn by the author) Scale 1:50*

5.4 Assessment of the Components and Project

The proposed architectural components are screens consisting of silk-based brick modules as permanent room dividers and cotton-and-viscose-based panels as portable components, defining semi-closed small rooms such as individual working spaces and conference areas. Cotton-and-viscose-based sound-absorbent wallcoverings were suggested for noisy office areas and meeting rooms. Furniture proposals contain the lightest silk-based stools in massive blocks and sound-absorbent viscose-based desk dividers made of panels; both are combined with aluminum profiles. The proposed sound-absorbent components with softer surfaces and higher porosity can be considered to enhance acoustic performance. The comparison of the various components can be seen in Table 10.

Table 10. *Analysis of the different components made of textile-waste-based composites*

Component	Material	Form	Construction Type	Type	Sound-absorbent
Screens *(150*300*100)*	Silk	Brick modules	Load-bearing structure	Permanent (Stable)	No
Screens *(500*500*30)*	Cotton /Viscose	Panels	Self-standing structure (sup. with alum. frame)	Portable /Mobile	Yes
Wall-covering	Cotton /viscose	Panels	Stuck to the wall	Permanent (Stable)	Yes
Furniture Stool/table	Silk	Massive blocks	Framed with aluminum profiles	Mobile	No
Furniture Desk divider	Viscose	Panels	Framed with aluminum profiles	Permanent (Stable)	Yes

Using sustainable materials can reduce the ecological impact of interior living and working spaces. Interior designers and architects should consider a life-cycle approach, the environmental audits due to each material production stage, use and disposal, the choice of either recycled or upcycled products, and prioritizing the use of bio-based and biodegradable materials. The holistic approach enables the assessment of both direct and indirect effects.

Global environmental challenges have been rising, and public awareness has grown. As a result, sustainability initiatives and products have been thriving among governments and corporations. On the other hand, establishing an interior design profession as a sustainable business enhances brands' image, and using sustainable materials indicates engagement to the environment.

Sustainable interior design should be better for human health first and increase productivity, and they are more affordable to build and maintain. Secondly, sustainable interior products use fewer fossil fuels, reducing global pollution while minimizing operating expenses. They lower the amount of water used and, more importantly, utilize waste as a resource to the maximum extent possible. Moreover, sustainable choices in the office reduce the number of materials with the minimum negative environmental impacts (Abdelaziz, 2010).

6 DISCUSSIONS AND CONCLUSIONS

Textiles are fundamental to the manufacturing sector, commerce, and retail in Europe, contributing significantly to economic growth and employment creation both in Europe and abroad. On the other side, European textile production and consumption habits have a significant and increasing detrimental impact on the environment across the world. These include excessive resource use, greenhouse gas emissions, and the dissemination of toxic chemicals, with adverse ecological damage to climate change and land and water competition.

Nevertheless, the linear system of textiles production and consumption is still an issue that has been confronted today. Fibers are derived from almost entirely virgin natural and fossil feedstock, and fast fashion items with a growing amount of synthetic and combined fabrics have become the mainstream. Thus, consumption patterns reveal a trend towards cheaper and short-lived items (Vercalsteren et al., 2019).

Although the European Community’s sustainability policies encourage shifting to sustainable and circular models for textile leftovers, recycling and upcycling those wastes are still rare. Today, much-worn clothing has been incinerated or disposed of in landfills, recycled textiles are mainly exported outside Europe or downcycled, recycling into lower-value goods. The linear system of the textile value chain causes the sector the most polluting and resource-demanding production and consumption systems, particularly throughout manufacturing and usage stages. Therefore, this thesis highlighted the importance of the transition to circular textiles by utilizing reuse, recycling, and upcycling.

Furthermore, construction and building sectors are responsible for 40% of carbon emissions and 36% of final energy use, which have the highest rate among various industries. 11% carbon footprint of the total is associated with manufacturing building materials and goods such as cement, steel, and glass. This research study focused on upcycling textile waste mixed with bio-based ingredients and converting them into sustainable, circular building products with minimal environmental harm. On the other hand, replacing the demand for newly produced materials, meaning that more greenhouse gases production, land, and resource use, with upcycled textile waste-based products, can positively contribute to the environment with low-carbon building stocks.

Theoretically, the main objectives were to grasp the current situation of the textile industry with the waste management in Europe and Italy, understand the extent of ecological harm of the textile leftovers and investigate the strategies for reusing them as a resource to create a circular building material made of textile waste. From the practical point of view, the primary purpose of this study was to produce new materials made from textile waste (100% silk, cotton, and viscose) and bio-based binders (starch-based glue) and evaluate their performances as interior building materials because of the low strength and durability of textiles against rainwater, snow, and winds.

In the experimental phase, a series of hands-on experiments were completed to create textile-waste-based samples in the SAPERlab in Politecnico di Milano. Pre-consumer leftovers of silk, cotton, and viscose were obtained from Ratti Spa Company, and the starch-based (successful in achieving material consistency) and the casein-based binders (failed to achieve material consistency) were prepared in the laboratory. Few simple types of equipment such as scissors, sieve, pan, and molds in different sizes and shapes were used during the physical experiments.

In the first phase, various material blends were created with starch-based glue and three fibers. Three series of experiments for each fiber (silk, cotton, and viscose) were completed by differentiating the parameter of fibers' sizes and forms, such as the small-sized (4-6 mm), medium-sized fibers (15-20 mm), and long strands (5-10 mm width). Every composition is relatively resistant and durable, having hard surfaces. However, the density differs; the silk-based composite is the lowest, and the cotton-based one is the highest.

In the second phase, the samples' capability to scale up was tested after defining the way of use in brick and panel forms to enable diverse combinations for screens, sound-absorbing wall coverings, and furniture in office interiors. The prototypes were prepared on a 1:2 scale using a 15x15 cm mold. The results show that the system can be upscaled successfully. It was essential to understand the capability of the new proposed system to scale up since the competitiveness of these sustainable and circular materials with the real world is a significant issue, In addition to measuring the acoustic performance of the produced textile-waste-based compositions.

In the third phase of experiments, five circular samples (diameter: ⌀10) were prepared for the impedance tube test to measure the sound absorption coefficient realized in the PSVL (Polimi Sound and Vibration Laboratory) Politecnico di Milano. The acoustic performance was tested for each silk, cotton, and viscose-based sample with different thicknesses and fiber sizes. The results show that the most promising sound absorption material is viscose-based composite with small-sized fibers (4-6 mm), which can be efficient for the low frequencies referring to the human voice in middle-sized closed rooms. However, using cotton and viscose fibers in the composite can improve the acoustic performance if the current samples' thickness, softer surfaces, porosity, binder concentration, and density are reconsidered.

In the last phase, the design project was proposed for an office interior in Palazzo del Capitano. Three different uses were suggested for office interiors, proposing a system using textile waste composites combined with aluminum profiles; screens (room dividers), wallcoverings, and furniture. Moreover, the importance of choosing green materials to promote sustainable office interiors and employees’ well-being and productivity were highlighted in this section.

Consequently, the potential use of textile waste fibers as an interior building material was highlighted to offer more green architectural applications by taking the circular economy model as an example, therefore, less resource use and carbon footprint and a more sustainable environment.

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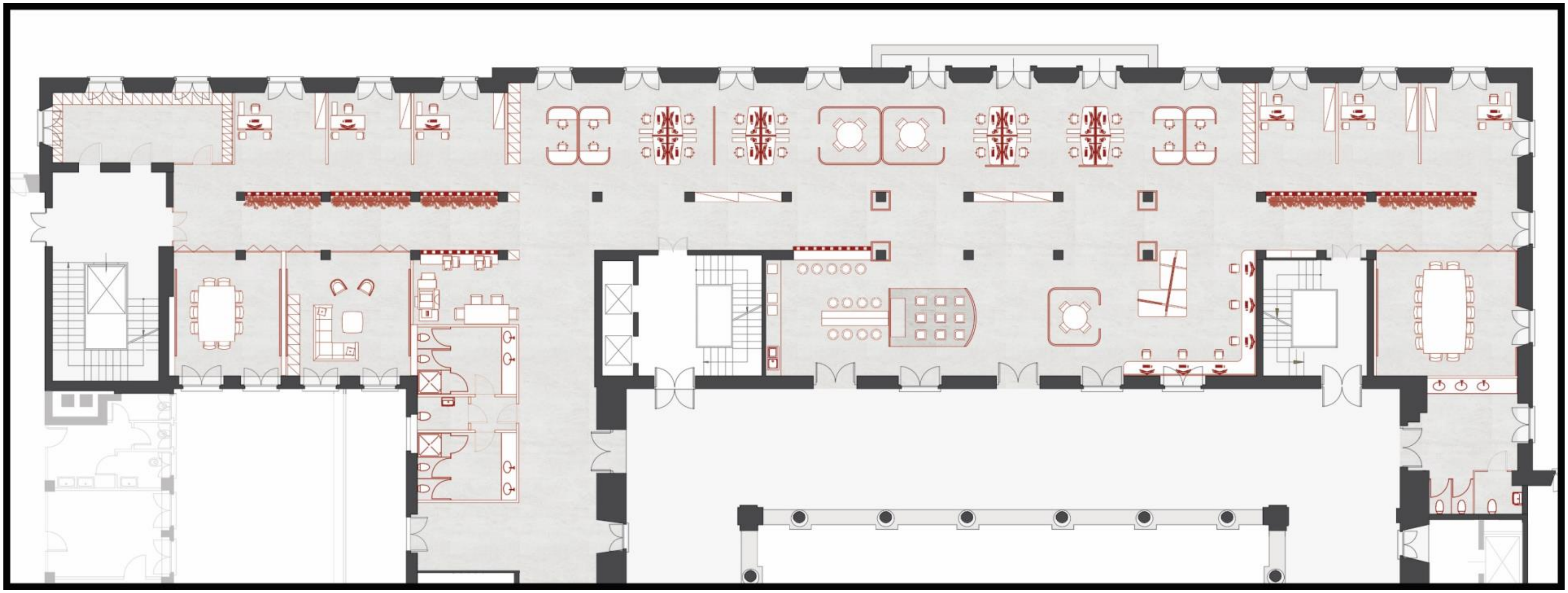
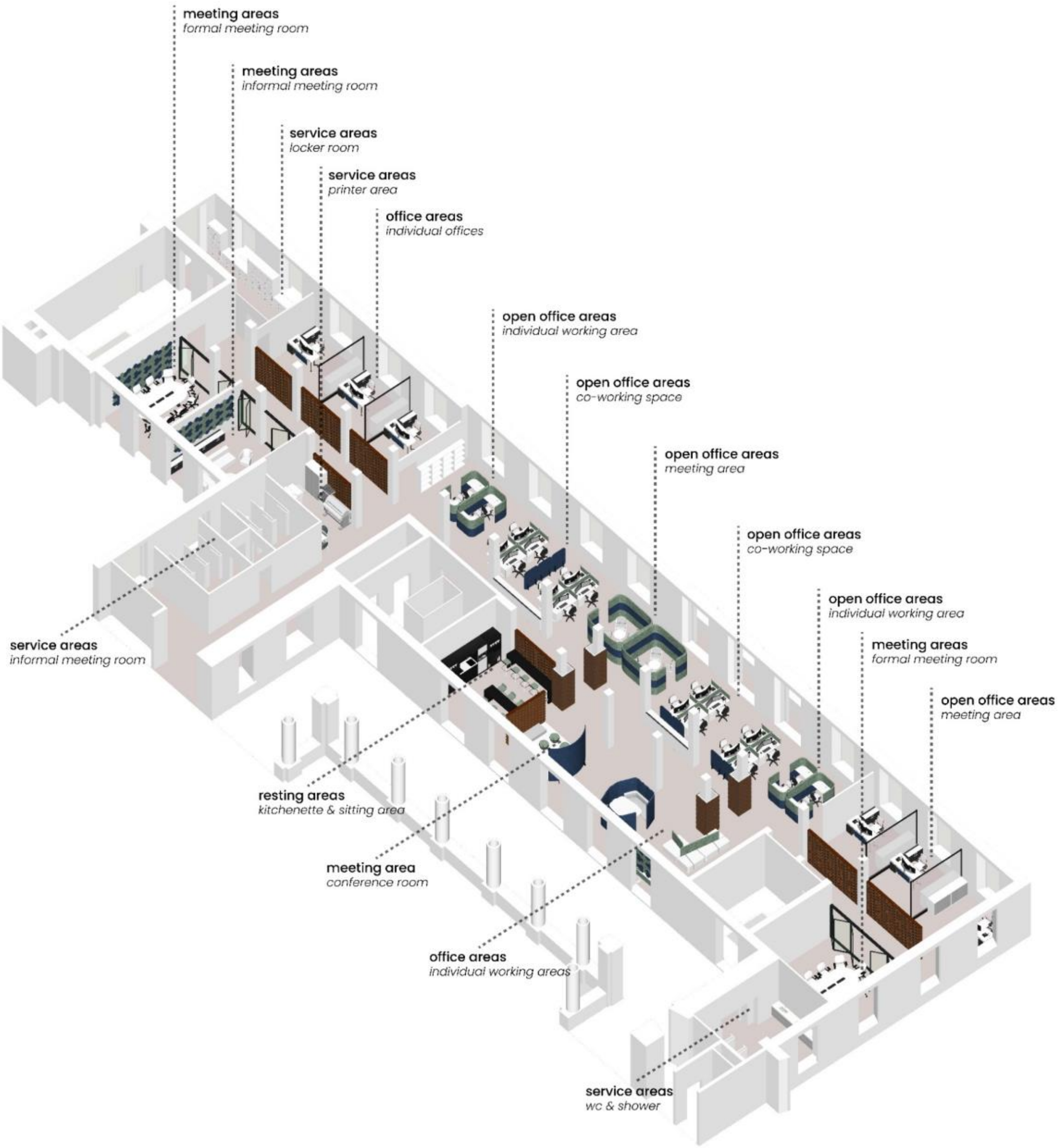
APPENDIX

Appendix 1: The proposed floor plan for the selected area (Scale 1:250)





Appendix 2: Axonometric view of functional analysis of the proposed floor plan for the selected area

🟤 Silk-based composite (in brick form)

🔵 Cotton-based composite (in panel form)

🟢 Viscose-based composite (in panel form)

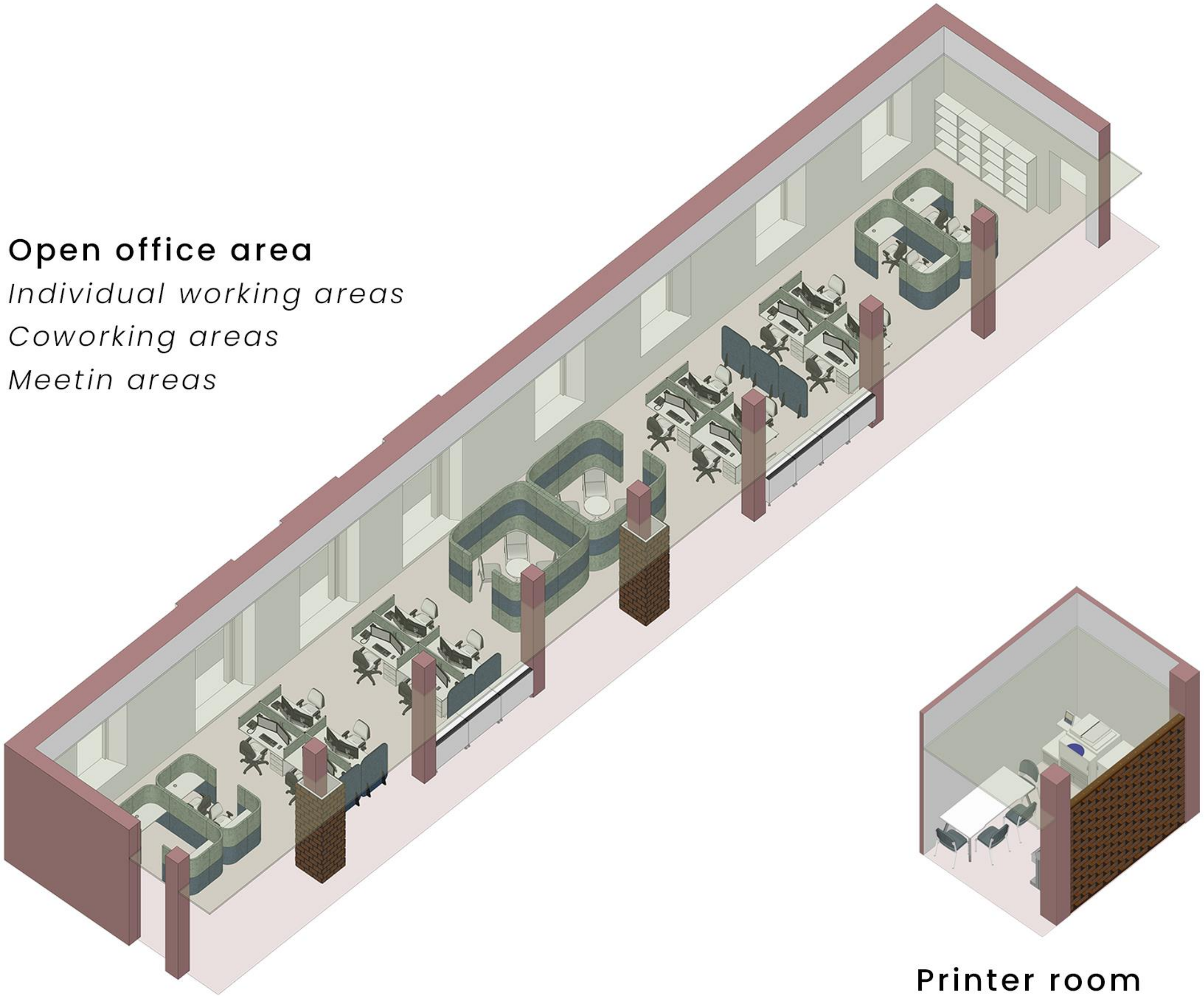
Appendix 3: Axonometric views for textile-waste based composite use in specific zones

Open office area

Individual working areas

Coworking areas

Meetin areas

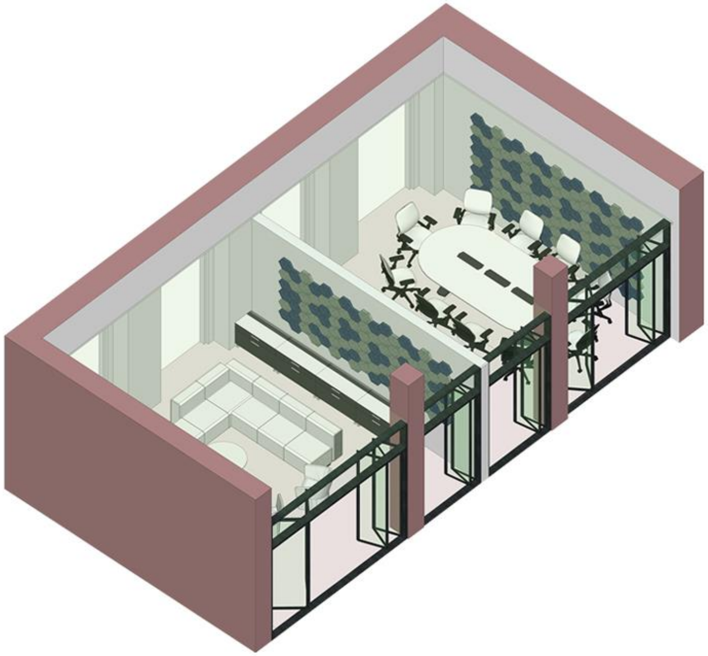


Printer room

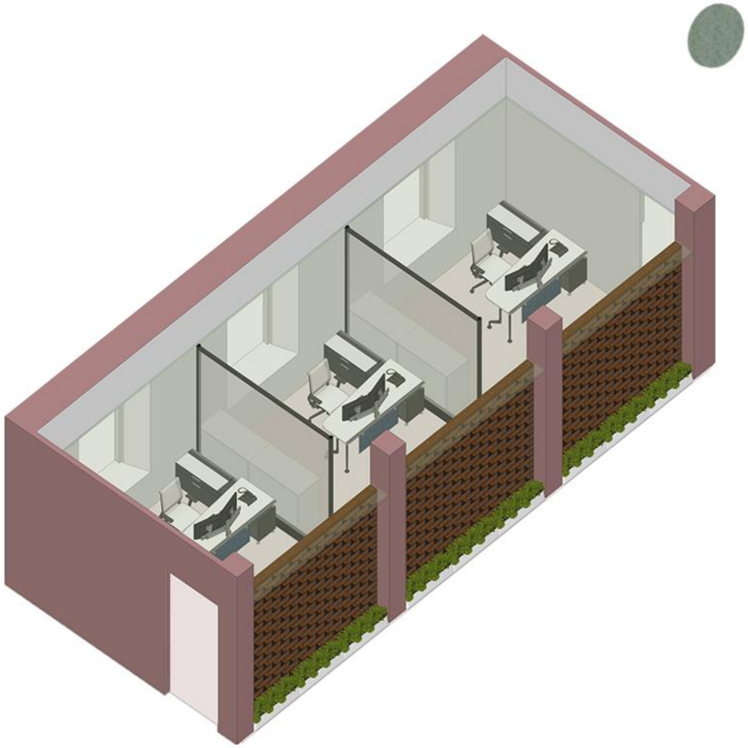
● Silk-based composite (in brick form)

● Cotton-based composite (in panel form)

● Viscose-based composite (in panel form)

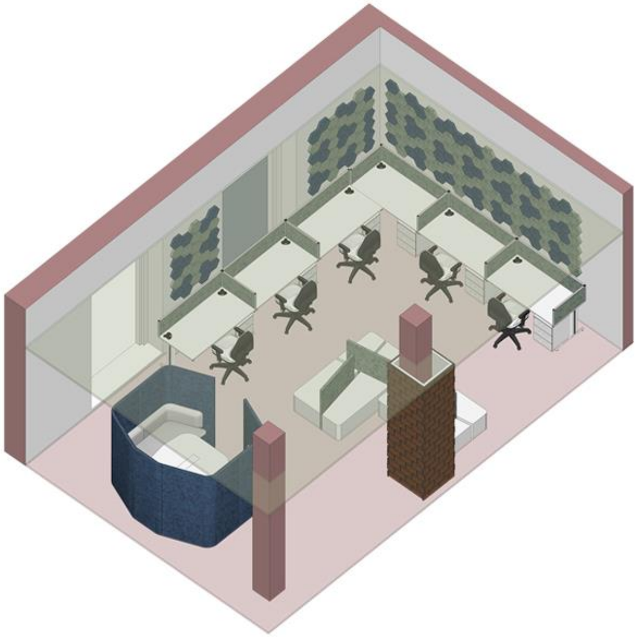


Formal & informal meeting rooms



Individual working offices

Kitchenette & conference area



Individual working &

co-working & meeting areas

Appendix 4: Perspective views for various textile-waste based composite use in the office interior

● Silk-based composite

● Cotton-based composite

● Viscose-based composite

Hexagon shaped wallcoverings (thickness: 30 mm)
Office desk dividers (thickness: 30 mm)
Furniture dividers for silent working (thickness: 50 mm)

Perforated brick-form screens (300*150*100 mm)
Panel form curved shape screens (arc: 600 mm)
Stool furniture with an aluminum frame (Ø= 500 & 400 mm)

Open office area

Hexagon shaped wall coverings (thickness: 30 mm)
dividers (thickness: 30 mm)
Furniture dividers for silent working (thickness: 50 mm)

Small conference area

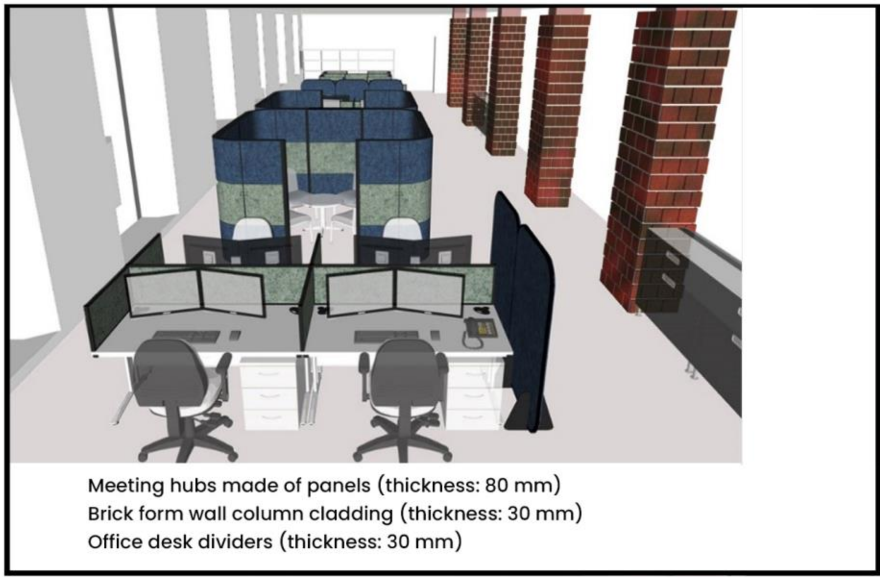
Perforated brick-form screens (made of silk-based Office desk composites) (300*150*100 mm)
Panel-form curved shape screens (arc: 600 mm)
Stool furniture with aluminum frame (Ø: ≈400-500 mm)

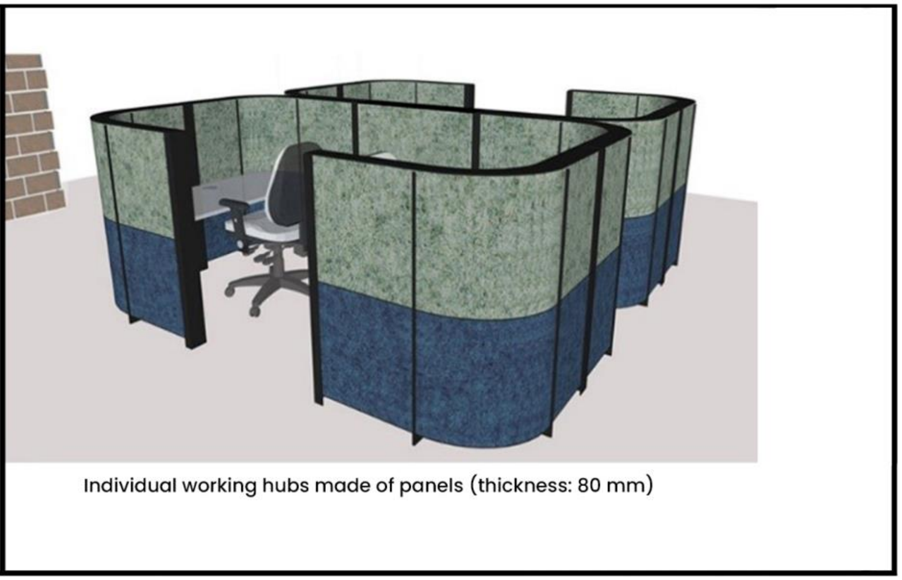
🔴 Silk-based composite

🔵 Cotton-based composite

🟢 Viscose-based composite

Open office area





Individual working hubs

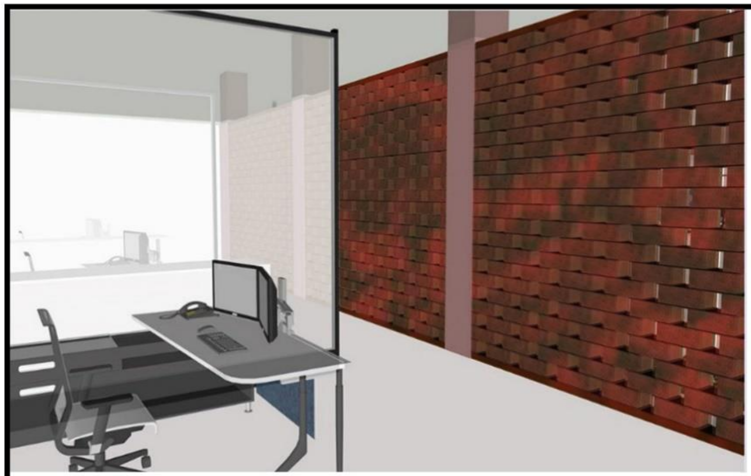
Meeting hubs made of panels (thickness: 80 mm)
Brick form wall column cladding (thickness: 30 mm)
Office desk dividers (thickness: 30 mm)

Individual working hubs made of panels (thickness: 80)

● Silk-based composite

● Cotton-based composite

● Viscose-based composite



Perforated brick-form screen (300*150*100 mm)

Perforated brick-form screen (300*150*100 mm)

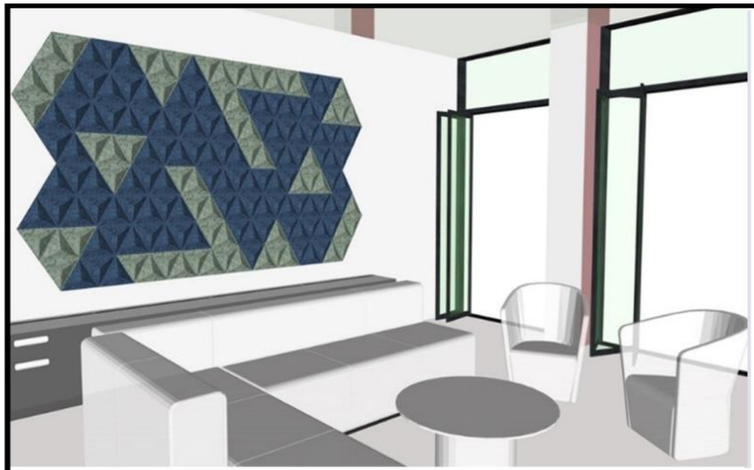
Individual office area

Perforated brick-form screens made of silk-based composite (300*150*100 mm)

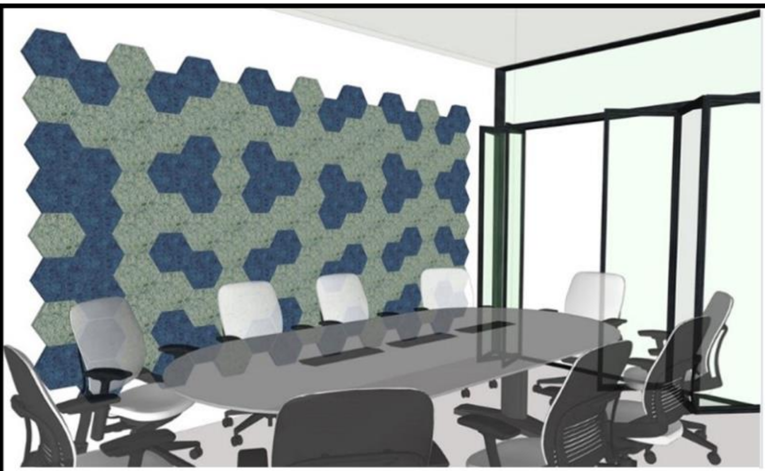
🔴 Silk-based composite

🔵 Cotton-based composite

🟢 Viscose-based composite



Three dimensional triangular shaped wall coverings
(thickness: 30 mm)



Hexagon shaped wall coverings
(thickness: 30 mm)

Informal meeting room

Three-dimensional triangular shapes wallcoverings
(thickness: 30 mm)

Formal meeting room

Three-dimensional hexagonal shaped wallcoverings
(thickness: 30 mm)