TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture,
Water and Environmental Engineering Research group

DIGITAL MATERIAL PASSPORT FOR CIRCULAR ECONOMY IN THE BUILT ENVIRONMENT

DIGITAALNE MATERJALIPASS RINGMAJANDUST TOETAVAS EHITUSKESKKONNAS

MASTER THESIS

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Tallinn 2024

AUTHOR'S DECLARATION

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THESIS TASK

Student: Sayed Shafqat Ali Shah, 212302EABM

Study programme: EABM03/18 - Environmental Engineering and Management main speciality,

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Consultants:

Thesis topic:

In English "***DIGITAL MATERIAL PASSPORT FOR CIRCULAR ECONOMY IN THE BUILT ENVIRONMENT***"

In Estonian "***DIGITAALNE MATERJALIPASS RINGMAJANDUST TOETAVAS EHITUSKESKKONNAS"***

Thesis main objectives:

1. To define the concept of digital material passport with respect to built assets within a circular economy through a review of the existing literature.
2. To investigate potential for digital material passports in construction industries of different countries (Estonia, Pakistan, Australia, Saudi Arabia, and Philippines) through semi-structured interviews with key stakeholders.
3. To determine recommendations for the use of digital material passports.

Thesis tasks and time schedule:

No	**Description**	**Deadline**
1.	Submission of thesis topic	01.02.23
2.	Literature review	21.02.23
3.	Research methodology	28.02.23
4	Interviews	31.10.23
5	Qualitative thematic content analysis	15.11.23
6	Writing of thesis	15.12.23

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ABSTRACT

Cutting waste and resource depletion requires creative solutions as we move toward a circular economy. Digital material passport (DMP), which offers a thorough record of a material life cycle, reusability, and recyclability, is one such approach. The potential of digital material passports to advance the concepts of the circular economy and lessen the environmental impact of the construction industry is examined in this thesis. A digital material passport can provide real-time data on the source, composition, and destination of materials, enabling a more responsible and sustainable approach to construction. It can also help to reduce the cost associated with materials, as well as the amount of waste generated. It explores the advantages and drawbacks of material passports as they currently exist and assesses their potential to spur construction material design innovation and improve supply chain transparency. A digital material passport's technological needs and design aspects, and implementation challenges, are also examined in this thesis. Additionally, it considers how stakeholders, such as authorities, industries, designers and economic factors could influence the acceptance and use of digital material passports. In the end, the purpose of this thesis is to offer insights into the creation and use of digital material passports as a tool for advancing a circular economy.

This thesis explores digital material passport implementation obstacles, possible benefits, and stakeholder views in the context of the circular economy in the built environment. Semi-structured interviews with stakeholders, including designers, suppliers, and construction industry experts, were conducted using qualitative research techniques. Patterns and insights were extracted from their narratives using thematic analysis.

The findings highlight the dual difficulties in successfully implementing DMP, which include both technological complexities and cultural changes in the building industry. Additionally, the study highlights the potential benefits that DMP may provide to businesses, such as new business models and lower carbon footprints. A closer look at how DMP is now being used in the Estonian construction sector reveals the sector is still in the experimental stages of implementing this cutting-edge instrument. Also, countries like Pakistan and Saudi-Arabia lack awareness of implementing material passports.

This study adds to the expanding body of knowledge on sustainable practices in the building industry and offers insightful guidance for practitioners, decision-makers, and scholars navigating the dynamic field of DMP in the built environment.

PREFACE

I am happy to deliver my master's thesis, which represents the end of my academic career. Without the assistance and cooperation of a lot of people, this thesis would not have been possible. It is the result of many months of meticulous research, analysis, and writing.

First and foremost, I would like to thank my thesis adviser, EMLYN DAVID QIVITOQ WITT whose knowledge, direction, and support were extremely helpful to me during this research. He provided me with incisive criticism and considerate input, which pushed me to go beyond my comfort zone and pursue excellence.

Additionally, I want to express my gratitude to the Department of Civil Engineering and Architecture (Environmental Engineering and management) faculty and staff at Tallinn University of Technology for your unfailing assistance, inspiration and support.

Keywords: Circular Economy, Digital Material Passport, Built Environment
Construction Industries, Environmental Impact, Standardization And Digitalization.

List of abbreviations and symbols

Abbreviation	
MP	Material Passport
BIM	Building Information Model
DT	Digital Twins
DMP	Digital Material Passport
LCA	Life Cycle Assessment
BCT	BlockChain Technology
CE	Circular Economy
IoM	Internet of Materials
DfD	Design for Disassembly

1. INTRODUCTION

1.1 Background

Nearly 40% of the world's energy use and one-third of its greenhouse gas emissions are attributed to the built environment, which also significantly contributes to resource depletion (Pérez-Lombard et al., 2008). To lessen these effects and build a sustainable future, the built environment must make the transition to a circular economy. A circular economy is an economic system that encourages the reusing, repairing, and recycling of materials and goods in order to reduce waste and resource depletion (Pomponi and Moncaster, 2017).

Material passports, which offer a thorough record of materials and their life cycle in the construction sector, are a crucial instrument in the circular economy. A material passport also offers a digital or physical document that details every material used in a construction along with its origin, make-up, and other pertinent details. It makes it possible to track and trace materials from use to disposal throughout their entire life cycle (Luscuere, 2017).

A comprehensive list that enumerates all the items, resources, and parts used in constructing a building or product, along with precise information about where they are located, giving each item its own identity apart from its present utilization. A material passport is a physical record of the composition and origin of a material, whereas a digital material passport (DMP) is a dynamic and accessible digital record that includes real-time information on materials, their properties, and environmental impact, which is critical for sustainability and circular economy efforts (Hoosain et al., 2021).

1.2 Potential benefits of DMPs

1. Improved material quality

Digital material passports may give a thorough overview of the quality of materials used in construction projects, including details on their characteristics, properties, durability, and safety. This can enhance customer trust and lower the likelihood of expensive recalls or liability claims by ensuring that material satisfies quality standards and are safe for use. Digital material passports can also make it easier to develop new and improved construction materials that fulfill certain performance standards by clearly describing the composition and qualities of materials (Luscuere, 2017a).

2. Recycling and reusing

Make it simpler to find possibilities for recycling and repurposing at the end of material lifespan, digital material passports can give information on the recyclability and reusability of materials used in many industries (Honic et al., 2019). This can open new prospects for the circular economy while also reducing waste and conserving resources. Digital material passports can aid the creation of creative recycling and repurposing technologies and systems by clearly identifying the materials used in a building or product (Honic et al., 2019).

3. Resource management

A relatively new idea in resource management, digital material passport, may have a big influence on how sustainable manufacturing and building processes are. A digital material passport is essentially a thorough document that details the origin and make-up of the materials used in a certain construction. Companies may use this information to better understand the resources they are consuming and to make more educated choices about how to use them efficiently (Luscuere, 2017).

One important advantage of digital material passport is that it may assist businesses in finding ways to cut waste and lessen the negative effects of their operations on the environment. Companies can find areas where improvements can be made to lessen their environmental impact by clearly knowing the origin and makeup of the products they are employing. They might be able to transition to employing materials that are recycled, sustainably sourced, or reused, for instance. This can lessen the quantity of trash produced during the building or manufacturing process and also lessen the negative effects of raw material extraction on the environment (Munaro and Tavares, 2021).

Digital material passports can aid in resource efficiency in addition to waste reduction and environmental impact reduction. Companies can find chances to utilize materials more effectively by having a comprehensive grasp of the origin and makeup of the resources they are utilizing. For instance, they could discover how to utilize a certain material more efficiently or how to switch out one substance for another that has a lesser impact on the environment. This may aid in lowering the overall quantity of resources needed to produce a good or construct a building (Honic et al., 2019).

4. Increased marketability

Digital material passports can provide you a competitive edge by proving your dedication to sustainability and openness. This can improve the marketability of goods and structures, especially in sectors where sustainability is a top priority. Material passports may assist in differentiating products and structures from competitors and attracting customers who are searching for more environmentally friendly and sustainably produced solutions by clearly outlining the materials that went into making them. Increased sales and customer retention, as well as improved brand awareness and reputation, may result from this (Walker, 2008).

1.3 Purpose and structure of this research

Significant methodological obstacles exist in research on digital material passports (DMP) for a circular economy in the built environment, including a lack of standardized procedures for analyzing DMP implementations, resulting in a gap between theory and practice. Furthermore, empirical research that takes into consideration geographical variations in DMP uptake and efficacy within specific regions is lacking. The dynamic nature of DMP technology, as well as worries about data protection, complicate research efforts even more. The purpose of this research is to fill these geographical gaps. It hopes to bridge the theory-practice divide and contribute to sustainable building practices in a variety of geographic situations within the built environment by doing so.

This research gives an in-depth look at the applications and challenges for implementation of digital material passports in the context of circular economy practices in the built environment. This study's research technique is qualitative in nature, with the goal of capturing opinions of stakeholders involved in construction industries in various countries Because the built environment is a worldwide problem, this study includes an international component by involving individuals from several nations.

The purpose of this study is to investigate the difficulties, advantages, and important factors related to the use of digital material passports in the construction sector. The following goals are the focus of the research:

- Analyze the obstacles preventing digital material passports from being implemented effectively.
- Examine the possible benefits of digital material passports for construction industry businesses.
- Examine the involvement and role of other parties, such as suppliers, designers, and construction companies.
- Examine how digital material passports are now used and regarded in various nations, taking into account the views of stakeholders who have experience in Australia, Philippines, Estonia , Saudi Arabia, and Pakistan.

By offering insights into the realities of implementing DMP in the construction sector, this study adds to the corpus of current knowledge. In order to promote a circular economy in the built environment, future policies, practices, and technology will be informed by an understanding of the obstacles, advantages, and stakeholder perspectives.

To explore the many subtleties of stakeholders' opinions on digital material passports (DMP), a qualitative method has been selected. The major components of the research technique include participants, data collection, data analysis and key findings. The study utilized a purposive sample technique to recruit individuals who reflected a range of occupations in the construction sector. Through qualitative interviews, contractors, designers, and construction experts were asked to give their perspectives.

Semi-structured, open-ended interviews were used to get detailed, in-depth answers from the participants. Ensuring informed consent and maintaining confidentiality were of utmost importance during the interview process. A qualitative research technique called thematic analysis was used to find recurrent themes and patterns in the participant response. This methodology facilitates a comprehensive investigation of the drawbacks, advantages, and viewpoints of stakeholders about DMP.

The investigation of DMP in the construction sector with an emphasis on Estonia, Australia, Philippines, Saudi Arabia, and Pakistan is covered under the study's scope. But the results can be context-specific, which would restrict their applicability to other areas or sectors of the economy.

This thesis is divided into 5 chapters, each of which focuses on a different facet of the goals of the research. Starting chapter consists of Introduction and overview of the thesis. The existing literature review will be discussed in detail in Chapter 2.

The research methodology is covered in detail in Chapter 3, which also provides an overview of the frameworks, instruments, and methods used to look into the effects and implementation of DMP. This chapter makes clear the methodical procedures followed in order to collect and handle data, guaranteeing the quality and dependability of the results. and stakeholder views, advantages, and problems are covered in this chapter.

The results are presented in Chapter 4, which is the core of the study. The difficulties in putting DMP into practice are discussed here, providing a thorough grasp of the obstacles encountered, which range from technological difficulties to cultural changes in the construction industry. Concurrently, advantages are revealed, illuminating revolutionary opportunities for companies and the industry as a whole. Insights from the literature review are also included with this analysis to give the subject a more complex viewpoint.
Chapter 5 is to summarize the whole master thesis and provide a conclusive statement and compile the whole research findings.

2. LITERATURE REVIEW

2.1 Circular economy in the built environment

The built environment, encompassing buildings, infrastructure, and construction activities, plays a pivotal role in resource consumption and environmental impact (Aghimien et al., 2019). Traditional linear approaches in the construction industry, characterized by "take-make-dispose," have led to resource depletion and increased waste generation (Amarasinghe et al., 2024).

The shift towards a circular economy in the built environment aims to revolutionize traditional approaches. Circular economy principles in construction involve extending the life of materials, decreasing waste, and conserving scarce resources (Benachio et al., 2020). This change in basic assumptions emphasizes material reuse, recycling, and sustainable construction practices. Circular economy practices in the built environment bring forth economic advantages beyond sustainability. By minimizing the extraction of fresh resources, circular strategies reduce the environmental impact of mining, manufacturing, and transportation (Morseletto, 2020). This resource efficiency not only contributes to environmental conservation but also leads to cost savings for construction projects. The economic benefits of circular practices extend to reduced waste disposal costs, lower material procurement expenses, and increased overall project efficiency (Ferdous et al., 2021).

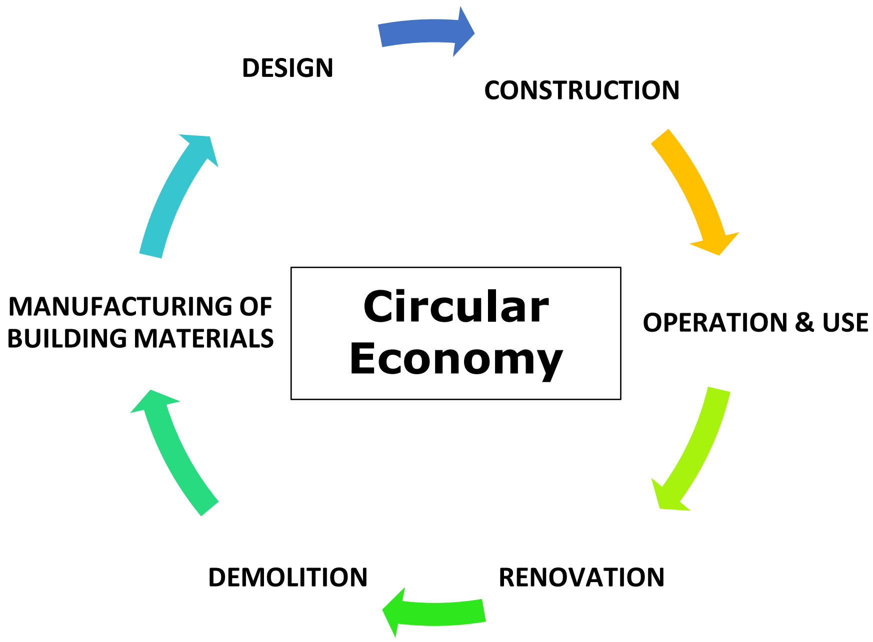

Figure 1 Circular economy in built environment adapted from (Huovila et al., 2019)

Beyond economic considerations, circular construction practices have notable social impacts. By prioritizing material reuse and recycling, construction projects contribute to community well-being. The reduction of waste output and landfill disposal enhances the quality of the local environment. Additionally, circular practices often involve community engagement and awareness initiatives, fostering a sense of responsibility and shared commitment to sustainable living (Al-Raqeb et al., 2023).

2.2 Digital material passports

The evolution of material passports can be traced back to the late 20th century, with the initial focus on operational expenses, quality of use, and technical characteristics in construction decision-making (Atta et al., 2021). The concept of material passports originated in Germany in 1997, initially focusing on operational aspects and technical qualities for construction decisions. As sustainability gained prominence, the material passport evolved to encompass more data, eventually leading to the development of Digital Material Passport (DMP) (Atta et al., 2021).These passports act like digital tags, storing detailed information on a product's materials. This allows for informed decisions throughout a product's lifecycle (Rumetshofer and Fischer, 2023).

Disassembling products becomes easier, facilitating reuse of components and efficient recycling of materials. Designers can use this data to create products with recyclability in mind, while consumers gain the power to choose sustainable options. By tracking materials and identifying inefficiencies, businesses can minimize waste and resource consumption. Overall, digital material passports provide the key to unlocking a more sustainable future by transforming our current "take-make-dispose" mentality (Hoosain et al., 2021). Material passports can be understood as a computerized system that stores all relevant information about materials used in the value chain, making the material's life cycle visible to all stakeholders (Kedir et al., 2021).

In recent years, there has been a global push for the adoption of standardized DMPs to facilitate cross-border material tracking and circular economy practices (Aguiar et al., 2019). Initiatives led by international organizations and collaborations between countries aim to establish a common framework for DMPs, allowing for seamless information exchange and promoting global sustainability goals. Standardization efforts include defining common data formats, interoperability protocols, and best practices for DMP implementation (Dey et al., 2022).

The digitalization of material passports has given rise to DMPs, introducing real-time insights into material composition, origin, and sustainability qualities. This transformation aligns with the industry's commitment to adopting novel solutions to meet evolving sustainability and circular economy objectives (Atta et al., 2021). DMPs play a crucial role in increasing resource efficiency, reducing waste, and facilitating the recovery and reuse of materials at the end of their life cycle (Honic et al., 2021). Stakeholders along the construction value chain are empowered by this real-time access to material properties. DMPs can help designers and architects choose materials that minimize environmental effect and maximize resource efficiency by taking sustainability factors into account (Atkinson et al., 2018).

Material circularity focuses on retaining and reusing materials throughout a building's life cycle (Singh et al., 2021). DMPs also have a great deal of promise for facility managers and building owners, allowing them to make well-informed decisions about restoration, maintenance, and, in the end to end-of-life deconstruction plans that emphasize material recovery and reuse. Collaboration and standardization within the construction industry are important due to the growing usage of DMPs. It is imperative to establish unambiguous and uniform rules for data gathering and management to guarantee precision, openness, and compatibility (Hoosain et al., 2021).

One of the defining features of DMPs is their ability to provide real-time insights into material composition. This ensures that stakeholders have up-to-date information about the environmental impact of materials, allowing for informed decision-making. The integration of sustainability metrics within DMPs enhances their functionality, making them not only a record-keeping tool but a dynamic resource for promoting eco-friendly practices (Van Capelle Veen et al., 2023).

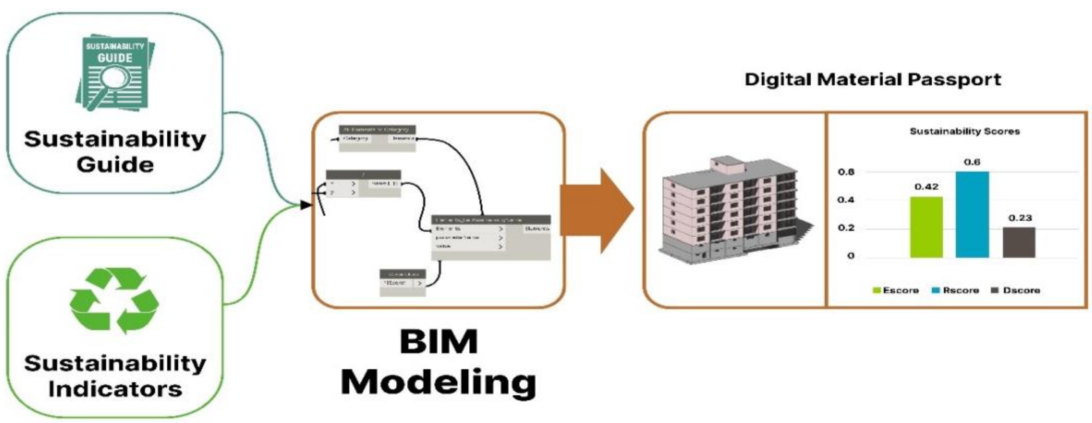

Figure 2 DMPs through sustainability metrics adapted from (Atta et al., 2021)

2.2.1 Functions of digital material passports

Digital material passports, also referred to as resource or object passports, serve as tools for describing material characteristics, recyclability, and reuse value (Yu et al., 2023). These passports offer a proactive means to monitor the worth of goods, impacting their recovery potential and overall value throughout the life cycle (Jensen et al., 2023).The information provided by DMPs facilitates innovation, offering recommendations for product design and enabling producers to transparently share the circular worth of their goods (Luscuere, 2017). Digital material passports' inherent information encourages innovation in the building industry. With the use of this data, manufacturers can openly convey the circular potential of their goods, providing useful information for product development and design (Luscuere, 2017). The prioritization of resource efficiency and circularity in the selection and utilization of resources is encouraged by the transparency that promotes informed decision-making.

Additionally, DMPs help to increase responsibility in the building sector. These digital documents assist in reducing any environmental and social risks linked with resource exploitation by monitoring the provenance and origin of goods, hence promoting responsible sourcing practices (Munaro and Tavares, 2021). This degree of openness encourages confidence and gives stakeholders the ability to make decisions that support sustainability objectives. Material passports can be used for purposes beyond just storing data. These digital technologies may actively direct the building process, which makes them an invaluable tool for streamlining workflows and reducing waste production (Takyi-Annan and Zhang, 2023).

Furthermore, DMPs can make effective demolition and disassembly possible at the end of a building's life, allowing precious materials to be recovered and reused (Alebachew et al., 2020). The construction industry's shift to a more circular economy is greatly aided by this strategy, which reduces the use of virgin materials and promotes sustainability on all fronts. But to fully utilize DMPs, cooperation and standardization within the building industry are required. To guarantee the accuracy, transparency, and interoperability of these digital records, it is imperative to establish clear and consistent rules for data collection and management. To optimize material passports' effects and promote the adoption of sustainable practices in the construction sector, stakeholders must cultivate a culture of data sharing and cooperation (Bellini et al., 2024).

2.2.2 DMPs in different sectors

Digital Material Passports, or DMPs, have revolutionary potential that goes well beyond the building sector. The fundamental concepts of DMPs—material transparency, recyclability assessment, and environmental effect monitoring—have great potential for usage in a variety of industries, even though their original application was on improving material transparency and encouraging sustainability in construction practices (Adisorn et al., 2021). By tracking the origin and makeup of raw materials, manufacturers may minimize their environmental impact and make educated sourcing decisions by utilizing DMPs. By guiding product design for recyclability and disassembly, DMPs could complete the material life cycle (Atta et al., 2021).

DMPs could have a significant positive impact on the automobile industry, which is known for its intricate supply chains and wide range of materials. Monitoring the composition of the vehicle's materials over the course of its life would help with responsible end-of-life handling, making it possible for parts to be recycled and disassembled quickly (Riesener et al., 2023). A major e-waste problem is created by the fast growth of electronic gadgets and their intended obsolescence. By giving comprehensive information on the materials used in each device, DMPs could provide a solution by facilitating responsible resource recovery and educated recycling procedures (Keshav Parajuly, 2017).

We may create a more comprehensive picture of the circular economy by encouraging cross-sectoral cooperation and modifying DMP principles for various industries. This integrated strategy encourages resource efficiency and conscientious environmental practices along the whole value chain, extending beyond specific industries as DMPs become more widespread (Adisorn et al., 2021).

2.3 Role of DMPs in circular economy

Digital Material Passports (DMPs) have emerged as indispensable tools, marking a paradigm shift in advancing circular practices within the built environment (Vahidi et al., 2024). Positioned at the intersection of digital innovation and sustainable construction, DMPs play a pivotal role in steering the industry towards circular economy principles and emphasizing their significance in revolutionizing how construction materials are managed and accounted for (Kebede et al., 2023).

One of the key advantages of DMPs lies in their ability to provide meticulous digital records of construction materials, ushering in a new era of transparency and traceability (Luscuere, 2017). This digital documentation goes beyond traditional record-keeping, offering a dynamic and real-time insight into the lifecycle of materials used in construction projects underscores the importance of this enhanced transparency, highlighting its role in promoting environmentally friendly material management practices. Luscuere (2017).

The DMPs not only pave a way for a broader goal of aligning construction practices with circular economy principles but also meet the requirements for effective material tracking (Munaro and Tavares, 2021). As construction projects increasingly recognize the importance of sustainability, DMPs serve as catalysts for change, encouraging the adoption of circular practices throughout the construction lifecycle. In essence, these passports become key enablers of a more holistic and environmentally conscious approach to construction (Dervishaj and Gudmundsson, 2024).

2.3.1 Environmental benefits, circular Design, and architecture

By lowering resource extraction, waste production, and energy consumption, circular solutions in construction, supported by DMPs, can decrease environmental impact (Morseletto, 2020). The problem of waste generation in the construction industry is addressed by the application of circular methods, in which DMPs are essential. The mitigation of the environmental impact of construction waste disposal is largely dependent on the promotion of material reuse and recycling, which is made possible by DMPs. Foster, (2020). When combined with DMPs, circular design principles have an impact on planning-stage architectural decisions. Using DMP data, designers and architects may choose materials with high circularity potential while taking durability, environmental impact, and recycling into account. Circular design and DMPs work together to create built environments that are resilient and sustainable (Aguiar et al., 2019).

With the incorporation of circular design concepts, DMPs are actively influencing the future of design rather than being passive stores of material data. This design philosophy prioritizes disassembly, reusability, and recycling when creating structures and products, keeping end-of-life considerations in mind. DMPs serve as more than just data trackers in this context. They also serve as guides and accelerators for the implementation of circular design techniques in the construction industry. Through the integration of material characteristics data, disassembly guidelines, and possible reuse alternatives, Design Management Packages enable designers and architects to make well-informed decisions at every stage of the design process, thereby reducing waste production and fostering a more sustainable built environment (Jensen et al. 2023).

A critical aspect of DMPs is their capacity to foster collaboration and transparency among stakeholders. Designers, manufacturers, contractors, and even end-users can access shared platforms, forming a network of information exchange known as the Internet of Materials (IoM). This collaborative approach ensures that all parties involved in the life cycle of a material have access to accurate and transparent data, promoting responsible material management practices (Hoosain et al., 2021).

2.3.2 Challenges and implementation of circular economy

While the concept of a circular economy in the built environment holds immense potential, its implementation faces challenges. Regulatory frameworks, industry standards, market incentives, and collaboration among stakeholders, including architects, engineers, contractors, legislators, and building owners, are crucial for successful implementation (Hoosain et al., 2021). Investment in research and development, along with innovation, is essential to advance circular technologies and practices (Ahakwa et al., 2023).

2.3.3 Advancements in DMP technology

Developments in DMP technology prioritize improving user interfaces and accessibility, indicating a paradigm shift toward democratizing access to vital material information. One of the most important developments in removing obstacles to accessibility is the emergence of user-friendly DMP platforms that are available via a variety of platforms, including online and mobile applications. The goal of this change is to involve a wider range of stakeholders, from end users to designers and constructors. DMPs encourage active engagement in and contribution to the circular economy by promoting inclusivity and ease of use (Panza et al., 2022). These user-centric innovations are not just decorative; they also seek to increase the efficiency with which material information can be retrieved and to create a feeling of mutual accountability among stakeholders in the promotion of sustainable material practices.

DMPs contribute to the circular economy by evaluating the overall weight of materials, assessing recyclability and waste potential, and determining the environmental impact (Van Capelleveen et al., 2023). This information is invaluable for gauging the material value of a building, planning sustainable waste management, and making materials publicly available (Meliha Honic et al., 2019). Moreover, DMPs can support thermal renovations, guide sustainable construction decisions, and foster a circular approach in the built environment (Panza et al., 2022).

2.3.4 Circular value of materials

Digital material passports record the beneficial effects that items have on their surroundings, going beyond the scope of typical environmental measuring instruments. They are in line with the Cradle-to-Cradle framework's tenets and cover a range of circular value dimensions, such as enhanced air quality and beneficial social effects (Luscuere, 2017). This paradigm offers a comprehensive approach to sustainability by highlighting the beneficial effects that materials have on the environment and society. In this context, material passports become indispensable tools for documenting and sharing data regarding the circular value of materials, offering insights that go beyond standard environmental metrics, like social benefits and improvements in air quality (Almusaed et al., 2021).

Regarding circular architecture, which is based on Cradle-to-Cradle principles, material passports are essential for accomplishing sustainability objectives. They provide vital details about the composition, Caliber, and state of building materials and act as identity documents for them. Material passports contribute to the larger goals of circular architecture in constructing resilient and sustainable built environments by assisting well-informed decision-making processes pertaining to material reuse.

2.3.5 Sustainable decision-making by Government and industry applications

To ensure a sustainable future, circularity must be implemented. Material passports are essential for encouraging material reuse, which is a fundamental component of circular activities. Digital Material passports help in the decision-making process regarding the acceptability of construction materials for reuse by acting as a means of gathering and classifying information about the materials. This strategy supports resource efficiency, reduces waste, and is consistent with the larger objectives of sustainability in environmental management and building.

DMPs are useful for industrial and governmental decision-making in addition to being beneficial for individual decision-making. The information supplied by digital material passports can be used by governments and environmental groups to inform policy decisions, provide alternate perspectives on green building certification systems, and evaluate the sustainability of construction projects. The incorporation of digital material passports into decision-making procedures improves the efficiency of resources, facilitates well-informed decision-making, and is consistent with wider sustainability goals (Yu et al., 2023).

2.4 Integrating DMP with other digital technologies

To enhance the effectiveness of Digital Material Passports, standardization is paramount. Sharing information through DMPs can be achieved by encouraging a circular economy in construction, digital technologies like Building Information Modelling (BIM), Blockchain, and Digital Twins can be integrated material passports throughout a building's life cycle (Atta et al., 2021). Applying these methods to already-existing buildings offers obstacles, even though they are crucial for designing and creating structures with circularity in mind. Future efforts, according to the research, ought to concentrate on creating a cohesive digital strategy and fostering stronger industry cooperation. Additionally, it identifies areas of promising future research, including the establishment of regional material banks and the implementation of regulations promoting circular construction practices (Banihashemi et al., 2024)

2.4.1 Building information modelling (BIM), Blockchain technology and digital twins

BIM, a widely employed tool in the architecture, engineering, and construction industry, offers three-dimensional modeling tools and processes. BIM enables efficient design, visualization, coordination of construction systems, and collaborative planning. Integration with DMPs provides detailed information about the qualitative and quantitative composition of building materials, supporting design optimization, and serving as a documentation tool (Adisorn et al., 2021).

The role of Building Information Modelling (BIM) extends beyond conventional design and planning. In the context of DMP integration, BIM serves as a catalyst for circular construction. The three-dimensional modeling capabilities of BIM enable designers to visualize and optimize circular design principles. This includes considerations for disassembly, material reuse, and end-of-life scenarios (Honic et al., 2019). BIM's ability to create a comprehensive digital representation of a building aligns with the goals of DMPs, ensuring that material information is seamlessly integrated into the entire life cycle of a structure (Çetin et al., 2023).

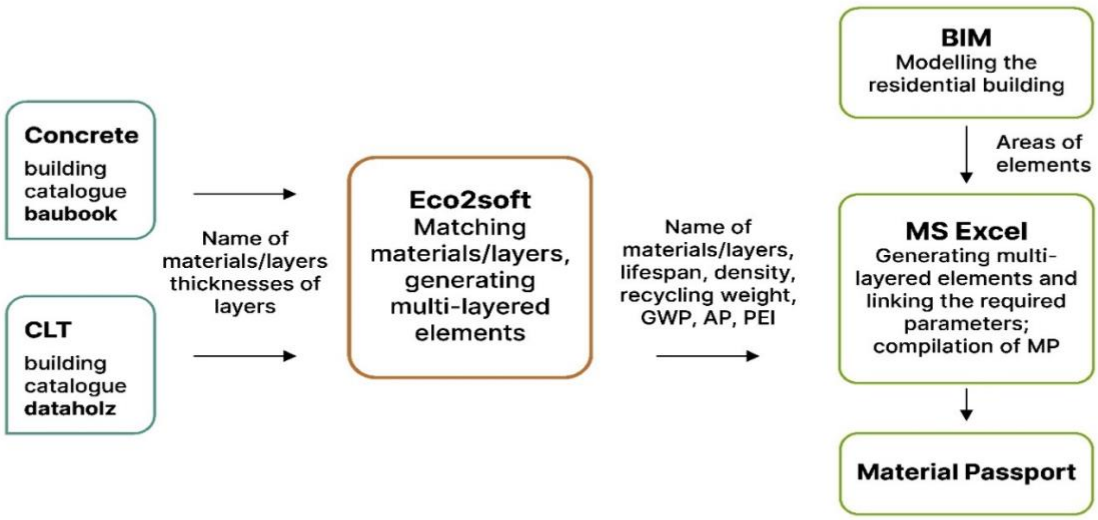

Figure 3 : Phases of BIM based material passport adapted from (Honic et al., 2019)

Despite the potential benefits of BIM in enhancing DMPs, challenges exist in terms of economic, organizational, and environmental barriers. Economic barriers may include the initial investment required for BIM implementation, especially for smaller construction firms. Organizational barriers may arise from resistance to change and a lack of awareness of the benefits of BIM-DMP integration. Environmental barriers may involve concerns about the ecological footprint of digital technologies. Overcoming these barriers requires a strategic approach, including targeted training programs, financial support, and advocacy for the environmental sustainability of digital tools in construction (Charef and Emmitt, 2021).

Blockchain technology (BCT) is emerging as a powerful tool in the context of the circular economy. It provides a decentralized and secure platform for recording and tracking materials throughout their life cycle. In the context of DMPs, blockchain technology ensures the transparent and immutable recording of material information, fostering trust among stakeholders and enabling traceability (Böckel et al., 2021).

One of the key advantages of blockchain technology in DMPs is its ability to enhance transparency and trust in material information. The decentralized nature of blockchain ensures that records cannot be tampered with, providing stakeholders with confidence in the accuracy and reliability of DMP data. This transparency is crucial for establishing a robust circular economy, where trust among participants is essential for the successful exchange of materials and information (Li and Wang, 2021a).

While blockchain technology holds great promise, challenges in its implementation include issues related to scalability, energy consumption, and standardization. Scalability challenges arise when implementing blockchain across large construction projects with numerous stakeholders (Kiu et al., 2022). Energy consumption concerns, especially in the context of environmental sustainability, need to be addressed through the development of more energy-efficient blockchain protocols. Standardization efforts are essential to ensure interoperability and seamless integration of blockchain with DMPs across the construction industry (Li and Wang, 2021b).

Digital twins, virtual replicas of the physical world, offer unparalleled insights into the performance of buildings and infrastructure. In the construction sector, digital twins can be employed to simulate performance, monitor conditions, and predict maintenance needs. Integrating DMPs with digital twins enhances the lifespan of building components through predictive maintenance, contributing to sustainable and efficient building management (Atta et al., 2021).

The integration of DMPs with digital twins introduces a new dimension to asset management in the built environment. By providing real-time information on the condition and performance of materials, DMP-enhanced digital twins enable predictive maintenance. This proactive approach reduces downtime, extends the lifespan of building components, and minimizes the need for resource-intensive repairs or replacements. The synergy between DMPs and digital twins aligns with the circular economy principle of maximizing the use and longevity of materials (Paramatmuni and Cogswell, 2023).

Several real-world applications highlight the effectiveness of integrating DMPs with digital twins. Case studies from construction projects demonstrate how this integration streamlines maintenance operations, reduces operational costs, and enhances the overall sustainability of buildings. As the technology continues to evolve, further exploration of its applications in diverse contexts, such as urban planning and infrastructure development, holds significant promise (Koutamanis, 2024).

2.4.2 Integration of DMP wit sustainability assessment tools

Various tools are employed to assess the sustainability of materials, including Life Cycle Assessment (LCA), Material Flow Analysis, Energy Certificates, and Environmental Product Declaration (EPD). Among these, LCA stands out as a comprehensive tool, evaluating products throughout their entire life cycle (Hossain and Ng, 2018).

Life Cycle Assessment (LCA) is a broad tool that assesses products across their entire life cycle, providing insights into their sustainability impacts. When integrated with material passports, LCA enables stakeholders to determine the characteristics and impacts of materials more efficiently (Larsen et al., 2022). This comprehensive approach aligns with the goals of circular economy practices, emphasizing not only the environmental impact but also the economic and social aspects of materials (Honic et al., 2019).

The integration of LCA with material passports ensures that sustainability assessments are a central component of decision-making processes in construction. Material passports provide the necessary data for LCA, offering detailed information about the composition, origin, and end-of-life considerations of materials. This integration enhances the overall sustainability of construction projects by guiding stakeholders towards environmentally responsible choices and supporting circular economy principles (Hoosain et al., 2021).

2.5 Research gaps and opportunities

A challenging task in the effort to advance circular practices in the built environment is the incorporation of material passports into sustainability evaluation methods. Protecting the sensitive information included in material passports—which contain detailed information about the make-up, provenance, and life cycle of materials—is one significant challenge. This gives rise to serious worries about the security and privacy of data, making it necessary to create strong protection mechanisms, moral standards, and regulatory frameworks to guarantee responsible data usage. Notwithstanding these obstacles, there are a lot of innovative options with the integration of material passports. While technological developments in data analytics and artificial intelligence have the potential to improve the effectiveness of sustainability assessments, technological innovations such as blockchain present intriguing options for safe and transparent data exchange.

By taking advantage of these opportunities, we can enable a smoother transition from conventional construction decision-making paradigms to a more comprehensive strategy centered on resource efficiency and environmental stewardship, paving the way for a more seamless integration of material passports into sustainability practices (Atta et al., 2021). To identify research gaps and potential for additional study around DMP implementation, it is imperative to comprehend these problems and opportunities.

1. Limited application studies

While there is a growing literature of research on the theoretical features of Digital material passport, there is a scarcity of detailed studies that explore the actual application of DMP in the real-world construction industry. Examining actual case studies and their outcomes might give useful insights into the challenges and benefits of applying DMP in the built environment. Also, gaps could be filled by those case studies and Success stories showing initiatives where DMPs decreased waste or increased efficiency would be strong inducements for broader adoption. On the other hand, by comprehending the implementation issues (difficulties in gathering data, resistance from stakeholders), the sector can create solutions for projects in the future. Lastly, case studies could demonstrate best practices in everything from communication protocols to data collection techniques, opening the door for more successful DMP tactics.

2. Standardization

When DMPs can interface with various supply chain and construction management systems, they function well. Because of this interoperability, data can be exchanged easily between different project stakeholders, fostering better teamwork, and breaking down information silos. Though limited, study on the issues and potential solutions related to DMP interoperability and the requirement for standardized data formats is essential for DMP implementation. The deployment of DMPs becomes a difficult and expensive task in the absence of well-defined standards and methods for integrating with current systems, which impedes their broad adoption throughout the construction sector. In addition to facilitating information transmission, standardizing data formats would allow DMPs to reach their full potential in terms of optimizing material consumption, cutting waste, and improving project efficiency.

3. Geographic variations

It is crucial to conduct comparative studies that assess the adoption and effectiveness of DMPs in several geographical settings. Legal frameworks, cultural factors, and market dynamics can all be considered to provide a more comprehensive knowledge of the opportunities and problems related to DMPs globally. This more comprehensive viewpoint will be essential for creating DMP implementation techniques that work well and can be adjusted to different geographical circumstances.

4. Economic viability

There has been little research into the economic viability of DMP deployment. Stakeholders may make more informed decisions by evaluating the return on investment, cost-effectiveness, and business models connected with DMP and determining prospective revenue streams or areas for cost savings, evaluating the direct and indirect financial gains, and tracking the overall cost of ownership over time are all components of comprehending the economic ramifications. Through thorough economic assessments, stakeholders can obtain significant understanding regarding the financial viability and sustainability of DMP implementation, enabling them to formulate strategic choices that are in line with organizational goals and resource limitations.

5. Data privacy and protection

There are significant worries regarding data security and privacy while using Digital Material Passports (DMPs). Keeping personal data safe on digital platforms is the main concern. Research on the moral and legal ramifications of DMPs is conspicuously lacking, despite the growing importance of data security and privacy. A comprehensive approach is becoming more and more necessary to address these concerns, especially considering the constantly changing rules and regulations pertaining to data privacy. Understanding the nuances of data privacy and protection within DMPs is essential for upholding compliance with existing laws and promoting confidence among users and stakeholders in a time when privacy issues are more sensitive than ever.

6. Policy and regulatory framework

Frameworks for regulations and policy play a crucial role in determining how Digital Material Passports (DMPs) are implemented and used. A thorough analysis of the legislative and policy frameworks that may support or hinder the broader implementation of DMPs is desperately needed. Data governance, standards compliance, environmental restrictions, and intellectual property rights unique to digital material documentation are only a few of the aspects that are covered by this examination. DMPs function as thorough logs of the whole lifecycle of a material, including its creation, use, and disposal. Consequently, to ensure compliance and promote innovation, it is imperative to evaluate how current regulations correspond with the special opportunities and problems presented by DMPs. Furthermore, it is crucial to actively engage with legislators and regulatory agencies to promote frameworks that support data security.

7. Small and medium sized construction firms

There isn't much information on how small and medium sized firms might use and benefit from DMP, even if bigger construction companies may have the capacity to do so. This gap may be filled by researching the viability of DMP for small and medium sized construction firms.

8. Life cycle assessment

The literature often discusses the possible sustainability benefits of Digital Material Passports (DMPs), with particular emphasis on decreased waste, increased resource reuse, and a more circular construction industry. Research that compares and measures the environmental and economic impacts of DMP-enabled circular practices vs traditional construction methods is critically lacking, nevertheless. This gap can be filled by integrating DMP data into Life Cycle Assessments (LCA), which can yield vital evidence for decision-making. LCA studies provide the ability to measure the environmental effects and possible cost savings linked with DMPs, which can offer strong backing for the widespread use of circular economy concepts in the building industry. This enhances the built environment's overall economic and environmental sustainability in addition to helping specific projects.

2.6 Significance of existing research to the research problem

Digital material passports (DMPs) track a product's materials throughout its lifespan to promote a circular economy. Existing research acknowledges challenges like a lack of standardized analysis methods and limited understanding of how DMPs work in different regions. My research aims to bridge this gap by studying DMP implementation in the construction industry across various countries, focusing on practical challenges and geographical variations.

This research explored how Digital Material Passports (DMPs) can transform the construction industry towards a circular economy. DMPs track materials used in buildings, making them easier to reuse and reducing waste. The study found that DMPs offer a range of benefits, including reduced greenhouse gas emissions and improved traceability of materials.

However, challenges exist such as a lack of standardization and the need for cultural shifts within the industry.

Overall, DMPs hold great promise for a more sustainable future in construction. Overcoming challenges like standardization and gaining wider industry acceptance are crucial for successful implementation. This research adds to the growing body of knowledge on DMPs, paving the way for a future where buildings are designed and constructed with a focus on sustainability and circularity.

3 RESEARCH METHODOLOGY

3.1 Introduction to Methodology

The study's methodology is explained, with a focus on digital material passports (DMPs) and circular economy practices in the built environment. To effectively meet the research objectives, the chapter explains the research design, participant selection criteria, data gathering methods, and data analysis procedures.

3.2 Research design

The decision to use a qualitative research design for this study was made due to the complexity of the research issue, which explores the various perspectives, difficulties, and experiences related to the implementation of digital material passports (DMPs) in the built environment. It is now impractical to conduct quantitative study aimed at the adoption of DMPs because they are not yet extensively used. When navigating the complexity involved in studying such occurrences, qualitative approaches provide a nuanced approach that works well. Qualitative methods explore the subjective perceptions and lived experiences of persons involved in the adoption and implementation of DMPs, in contrast to quantitative approaches which primarily concentrate on numerical data and statistical analysis (Creswell and Poth, 2018).

This study intends to identify the underlying meanings, motives, and contextual elements that affect stakeholders' perceptions and behaviors linked to DMP adoption by utilizing qualitative research approaches. Researchers may fully grasp the benefits and challenges related to DMP implementation by capturing the richness and depth of participants' perspectives through in-depth interviews and qualitative data analysis. The investigation of various viewpoints and voices within the built environment, such as those of architects, engineers, contractors, legislators, and other significant stakeholders, is also made possible by qualitative research. Qualitative approaches provide a comprehensive lens through which to analyze the dynamic interplay of elements affecting the move towards more sustainable and efficient construction practices, by embracing the diversity and complexity inherent in the adoption of DMPs.

The exploratory nature of the research aims, and the qualitative research strategy selected for this study aims to reveal themes, patterns, and insights that might not be immediately discernible from quantitative methods alone. Qualitative research offers to shed light on the complex processes of DMP adoption and educate strategies for fostering its effective implementation within the built environment through its emphasis on depth, context, and participant perspectives.

3.3 Research process

The goal of the methodical research process is to investigate the intricacies of Digital Material Passports (DMPs) in the built environment. In order to provide a foundational understanding of the topic, it starts with a thorough analysis of the body of prior research and research questions. The research process, which includes participant selection, data collecting, and analysis, is then described. Interviews are the main method of gathering data, and participants are carefully selected. The interviews are transcribed and processed for analysis. To find reoccurring patterns and themes in the interview data, thematic analysis is used. Concurrently, a thorough examination of the body of existing literature enriches the conclusions. At the end of the process, opportunities, problems, and suggestions related to DMP adoption and implementation in the construction sector are identified. The process of investigating the potential effects and difficulties of Digital Material Passports in relation to sustainable building techniques is depicted in the following image.

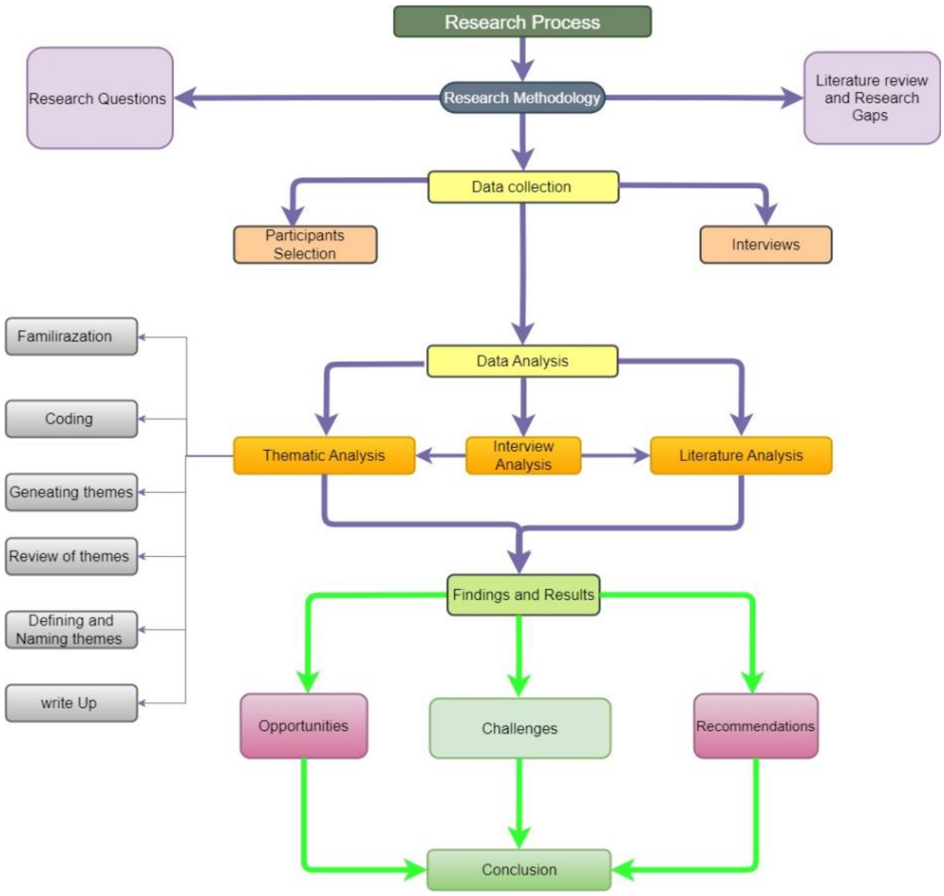

Figure 4 Research Process by author

3.4 Participant selection and Sampling

To obtain firsthand knowledge and expertise on the subject, participants were chosen from construction companies and organizations that were or planned to be involved in the development and implementation of material passports and also who were motivated to contribute to the minimization or reduction of waste in the industry for a sustainable future. The study sought to gather complex viewpoints and experiences pertinent to the research goals by focusing on stakeholders who were actively involved in DMP doption.

To make sure that the participant pool included a variety of viewpoints and experiences connected to the implementation of DMPs, purposeful sampling was utilized. This sampling technique enhanced the range and depth of data gathered by allowing the inclusion of people with different degrees of participation in the creation, application, and use of material passports.

Several criteria that balanced the practical constraints within the study's scope with the depth of data obtained led to the decision to limit the number of participants to 10. First off, gathering, transcribing, and analyzing data takes a lot of time when using qualitative research techniques like in-depth interviews. The study sought to guarantee that author could adequately examine and assess each participant's viewpoints and experiences by restricting the number of participants.

The choice of ten participants was also influenced by the data saturation concept. The theoretical saturation point is achieved when fresh participants or data points no longer yield significantly new insights or information. This is known as data saturation. In order to attain data saturation more quickly and guarantee that the study included a wide variety of viewpoints and experiences without needless duplication, author concentrated on a smaller sample size.

Additionally, several factors were considered when choosing the participants from Pakistan, Saudi Arabia, Estonia, Australia, and Philippines . First and foremost, these nations were picked in order to offer geographic diversity and gather perspectives from various legal, cultural, and economic situations. The study aimed to investigate the ways in which national regulations, industry practices, and socio-cultural norms impact the adoption and execution of DMPs by incorporating individuals from several nations.

Second, the selection of Pakistan, Saudi Arabia, Estonia, Australia, and Philippines was based on the differences in the countries' adoption of digital innovation and sustainable building techniques. Estonia is an intriguing case study for DMP adoption because of its reputation for taking a progressive stance toward innovation and digitalization. Saudi Arabia offers special potential and challenges for the implementation of DMPs because it is a significant player in the construction industry with ambitious development initiatives. Conversely, Pakistan provides valuable perspectives on the implementation of DMPs in the context of developing economies and dynamic regulatory environments. Australia's advanced digital innovation and use of sustainable building techniques led to its selection as a case study. Australia, known for its state-of-the-art technology and eco-friendly projects, provides insightful information on sophisticated digital adoption and creative building techniques. Researchers can learn more about how developed economies use digital management practices into their building industries by looking at Australia's approach. In order to emphasize its distinct place in the context of digital innovation, the Philippines was selected as the subject of another case study. For the implementation of digital construction management procedures, the Philippines offers unique potential and challenges due to its status as a growing country with dynamic regulatory frameworks. Researchers can get important insights on digital technology adoption in developing countries and navigating fluctuating regulatory regimes by examining the experience of the Philippines.

3.5 Data collection

Individual, one-on-one interviews were used to collect data; these interviews might be done in person or virtually using video conferencing software. Based on an expert review and a survey of the literature on material passports, semi-structured interview instructions were created. The interview questions were crafted to go into a range of topics, such as the advantages and difficulties of physical passports, the variables that impact their acceptance, the ways in which digitalization might bolster the concepts of the circular economy, and tactics for effective execution.

3.4.1 Interviews

The semi-structured interview questions were developed based on a review of literature on material passport and expert review. Table I shows the details of interviews conducted during the research period.

Interviewee Number	Date of Interview	Country	Occupation	Format of Interview
1	12/04/2023	Estonia	Engineer	Video call (Zoom)

2	16/04/2023	Saudi Arabia	Construction Company owner /Supplier	Phone call audio recording
3	17/04/2023	Estonia	Engineer	Video call (Zoom)
4	18/04/2023	Estonia	Engineer	Video call (Zoom)
5	21/04/2023	Pakistan	Construction Company Owner/Supplier	Phone call audio recording
6	21/04/2023	Australia	Designer /Engineer	Phone call audio recording
7	22/04/023	Philippines	Designer	Video call (Zoom)
8	22/09/2023	Estonia	Engineer	Audio call (Zoom)
9	21/09/2023	Estonia	Associate Professor	In-person interview
10	29/09/2023	Saudi Arabia	Material Design Engineer	Video call (Zoom)

Table 1. Interviews

3.4.2 Interview questions

The questions were deliberately designed to explore the complex terrain of material passport adoption in the building sector. Every question functions as a strategic probe, seeking to uncover unique viewpoints, experiences, and ideas from participants. These inquiries traverse the difficulties of DMP adoption, from finding implementation barriers to clarifying potential benefits across multiple industry sectors. Through an examination of the present application, essential specifications, and intended content of material passports, participants are urged to consider their own experiences and provide insightful suggestions for next implementation tactics.

The questions were as Follows.

1. What challenges do you see in implementing a material passport?
2. What are the potential benefits of a material passport for companies, Construction Firms, Contractors, suppliers, and Designers?
3. How is the use of a material passport in your Construction Industry or in your country?
4. What are the key requirements for successful implementation of a material passport?
5. What kind of information do you think should be included in a material Passport?
6. What role do you think standardization and Digitalization can play in the implementation of material passports?
7. What is your overall opinion on material passports?
8. Do you have any suggestions or recommendations for the successful implementation of a material passport?

3.6 Ethical considerations

Ethical considerations were considered in this study. Participants were provided with an information sheet explaining the purpose of the study and their rights as participants. Informed consent was obtained from all participants prior to the start of the interviews. Participants were informed that their participation was voluntary and that they could withdraw at any time.

4. RESULTS AND DISCUSSIONS

4.1 Data analysis

The interviews were conducted Online, In-person and on phone call and were transcribed and analyzed using thematic analysis.

Participants were experienced in the construction industry and had a good understanding of material passports. The participants from countries like Saudi Arabia and Pakistan had not much information about DMP, but the more experience in construction industry and efforts towards circular economy and sustainability encouraged them to explore DMP with motivation. Analyzing qualitative data involves closely examining a set of texts, such as interview transcripts, to identify common themes, topics, and patterns of meaning that emerge. This process, often referred to as thematic analysis, follows a structured approach typically consisting of six steps: familiarization, coding, generating themes, reviewing themes, defining and naming themes, and writing up. By systematically following this process, researchers can avoid confirmation bias and ensure the reliability and validity of their analysis.

4.2 Coding of the data

To ensure accuracy and completeness of the data, each interview recording was meticulously transcribed manually as part of the transcription and coding procedure. The text that had been transcribed was then carefully examined to look for reoccurring themes, trends, and ideas pertaining to material passport. The important ideas and difficulties present in the conversations might be extracted thanks to this manual examination. To facilitate systematic data administration and analysis, a unique code was then issued to each recognized theme or notion. By collecting the subtleties of participant responses by hand, this manual method guaranteed accuracy and comprehensiveness. Using Microsoft Office products, the data was manually coded, enabling the establishment of an organized framework for additional research and interpretation. Meaningful insights into the impressions were generated thanks to the meticulous coding process. Table 2 represents coding of the data.

Codes	Themes	Description/Themes including sub themes	Frequency of Themes/Codes Across Interviews
C1	Challenges	Technical **challenges** in material passport implementation (Standardization, machine-readability, compatibility)	67/10
C2	Implementation	Cultural challenges in material passport **implementation** (Change in perception, shift in understanding of built environment)	142/10
B1	Buisness models	New **business models** for companies with material passport (Service-based models, engagement in material use/operation)	6/2
B2	Buisness	Expansion of **businesses** in construction and real estate sector with material passport	3/1
B3	Carbon Foot print through MP	Assistance in measuring and reducing **carbon footprints through material passport**	13/4
CF1	Construction Firms	Involvement of **construction firms** in incorporating reused materials and components	46/10
CF2	Standardization	New **standardization**, testing, and quality assurance regime for construction firms	26/8
D1	Designers	Interest in "Design for Disassembly" (DfD) among **designers**	28/6

D2	Design for for Disassembly	Incorporation of measures in **design for efficient disassembly and reuse**	1/1
U1	Construction Industry in Countries	Experimental and pilot project stages of material passport in the **Estonian ,Australian , Saudi , Pakistan, Philippines construction industry**	14/10
U2	Main stream	Material passport not yet **mainstream**; students beginning to learn about MP and **circular economy**	9/3
KR1	Requirement	Standardization as an essential **requirement** for material passport implementation	51/10
KR2	New Standard	**New standards**, testing, and certification procedures needed for safe and guaranteed **reuse**	22/8
KR3	Standardization through Taxes	Strong incentives needed before **standardization,** possibly through increased disincentives **(taxes)**	6/3
I1-I2	Information	**Information** Included in material passport and Maintenance	102/10
SD1-SD3	Digitalization	Standardization and **Digitalization** in Implementation	91/10
En1	Environmental Benefits	Environmental Benefits	66/9
EA-1	Environmental Benefits	Education and training	27/7
AU1	Awareness and understanding	Awareness and understanding	34/10
O1-O2	Overall opinion	Overall opinion	10/10

SR1-SR2	Suggestion and Recommendation	Suggestion and Recommendation	19/10

Table 2. Coding of the data

4.3 Emerging themes

Several themes were emerged from Interviews including:

1. Technical and cultural challenges

The implementation of material passport (MP) presents a combination of technological and cultural challenges. There are substantial technological obstacles in standardizing MP for machine readability and compatibility with a variety of software programmes (C1). These technological challenges are further compounded by the development of standardized testing methodologies, quality assurance systems, and materials exchange platforms (C1). Buildings as transitory material repositories need to be seen differently in the construction business on a cultural level (C2). This influences how buildings are planned, used, and valued, requiring a greater understanding of the built environment (C2). The secret to effectively tackling the challenges of MP implementation is to combine technological and cultural concerns.

2. Potential benefits for companies

The material passport (MP) (node B1) has the potential to help businesses, which highlights the revolutionary possibilities they have for the corporate environment. By highlighting service-oriented strategies in line with certain material groups or components, such doors, windows, and vertical mobility services, MP provides access to cutting-edge business models. Real estate and construction companies may need to grow their operations to include activities connected to material and component removal, destruction, and reuse as a result of this transition towards service-based models.

Moreover, the implementation of MP makes it easier for enterprises to assess and reduce their carbon footprints (node B3). This highlights the potential of MP as a useful instrument in accomplishing environmental goals and is in line with more general sustainability aims. Incorporating MP strategically into corporate processes may help reduce carbon emissions overall, which is a big step towards the construction and real estate industries adopting more environmentally friendly and sustainable practices.

3. Involvement of construction Firms (Reuse, Standardization, Testing)

A substantial reconfiguration of business lines (node CF2) arises with the adoption of a material passport (MP). Conventional responsibilities alter when suppliers move from extraction- or manufacturing-focused organizations to more platform-oriented organizations that prioritize the interchange of materials. In this evolving environment, contractors may play a significant role as important providers of construction materials. This dynamic change demonstrates how MP has the capacity to improve sustainability and completely reimagine the business environment in the construction sector.

4. Role of designers in design for disassembly and efficient reuse

The interviews highlight how designers are very interested in the idea of "Design for Disassembly" (DfD) (node D1). This method entails implementing certain design features to facilitate disassembly procedures and encourage effective material and component reuse. In keeping with sustainable design principles, the interviews emphasize how important designers are to advancing the circular economy in the building industry.

The personal observations made by specialists in the field shed light on the realization that Design for Disassembly (DfD) is a workable approach (node D1). It becomes clear that this method pushes for a significant paradigm change in the way that designers think about their work, encouraging them to adopt a more circular and sustainable way of thinking about how to shape the built environment.

5. Implementation of material passport in the industry and country (International perspectives)

Participants pointed out that the time and money-consuming process of establishing material passports required extensive data organization and gathering activities. They also highlighted that implementing material passports could be difficult when working with various supply chains because it can be difficult to obtain data from the several parties involved. Also, countries like Pakistan have poor data transparency regarding materials due to more political involvement in major construction projects and stakeholders.

The fact that MP is used differently in other nations offers a global perspective on their application. For example, in Estonia, the construction sector has not yet embraced MP and is still in the experimental and pilot project stages. In the meanwhile, there are differences in the degree of MP acceptance and integration into building practices across Australia, Saudi Arabia, and Pakistan. There is a continuing worldwide trend towards investigating the possibilities of MP on a global scale, as evidenced by the awareness and education regarding the concepts of MP and the circular economy in the construction sector.

6. Key requirements of successful implementation on DMPs

A crucial element for the effective implementation of digital material passport (DMPs) centers on the creation of two tiers of standardization, as discussed 26 times. First and foremost, standardizing MP themselves (node SD1) is essential to guaranteeing both their findability and interoperability with a variety of software programmes. A participant in the interview stated, "Without standardized DMP, the effectiveness of the entire system is compromised, hindering seamless integration with existing software." Second, there has to be a strong standardization effort for materials (node SD), which includes frameworks for certification, testing, and procedures.

The need to ensure the safe and secure reuse of materials and components within the circular economy framework highlights the importance of this two-layered standardization. Strong incentives, such higher disincentives like tariffs on the mining of raw materials, became prevalent prior to standardization (node KR1). Participants emphasized that in order to encourage a change towards appreciating and recycling materials, such actions are crucial. Implementing DMP successfully also depends on careful impact monitoring, facilitating effective material transfers, and collaborating on research projects supported by business collaborations. To fully appreciate DMP potential benefits in the construction industry, a thorough strategy is essential.

7. Information included in DMP

Upon examining the coded data, the category corresponding to the data included in material passport (DMP) became clearly apparent (node I1). The need to include all relevant information in DMP—such as material composition, sources, historical usage, strength, thermal and fire performance, safety, and hazard data—was often underlined. The dynamic character of this data, which changes over time and with usage, was emphasized by the participants. This emphasized the necessity of ongoing DMP maintenance to guarantee data accuracy. This theme's task goes beyond simply compilingMP initially; rather, it encompasses the continuous effort to maintain their correctness during their lifetime.

8. Standardization and digitalization of DMPs

A key subject emerged in the discussion on the digitization and standardization of material passports (DMPs) (node SD1). In terms of the materials themselves as well as the standardized content inside DMP, participants underlined the vital role that standardization plays in guaranteeing the efficacy of DMP. Since the current building business is inherently digital, DMP compatibility depends on their digital character. Participants did, however, recognise the difficulties currently facing format standardization, particularly with regard to ensuring utility and interoperability across various digital platforms and applications.

The lack of universal standards for DMP (node SD2) was identified by participants as a major obstacle that hinders the widespread adoption of DMP. The current lack of standardization limits the use of material passports in the business, raises concerns about their worth, and creates confusion by making it difficult to compare and independently evaluate the data provided in them. This problem is especially severe for businesses that operate in many nations, like Pakistan, or areas, where various laws and reporting standards might make it difficult to create a uniform material passport.

A few participants projected what they thought the DMP environment may look like in the future (node SD3). The widespread adoption of circular economy ideas may lead to the necessity for enterprises operating sectors or regions. Additionally, it was suggested that decentralized technology like blockchain might help improve the accuracy and security of real passport data. Participants noted significant obstacles in spite of these opportunities, such as the need for businesses and consumers to have a better grasp of material passports. The increasing acceptance of digital access to material passports was deemed crucial for small company owners and diverse building industries.

9. Environmental benefits

Environmental benefits emerged as a prominent theme (node En1) in the discussions on material passport (DMP). The benefits of DMP for the environment were emphasized by the participants, who also emphasized how they might reduce waste and promote the development of a circular economy. DMP was crucial in lowering the environmental impact of building projects since they made it easier to identify and use sustainable and recycled materials. This might thus result in a decline in the market for raw materials, which would cut energy use and manufacturing-related greenhouse gas emissions.

The significance of DMP in encouraging environmentally responsible corporate practices was also emphasized by the participants (node B3). By giving companies a way to track the origin and end of life of materials, DMPs promote the use of sustainable practices. Thus, in keeping with eco-friendly ideals, this may help lower the amount of rubbish dumped in landfills. Additionally, MP was viewed as a tool to improve openness and accountability in the construction industry, benefiting clients, authorities, and other stakeholders.

Some participants offered a forward-looking viewpoint, speculating that the adoption of MP would play a key role in facilitating the shift to a more circular economy (node B4). Materials would be recycled and reused in this envisioned circular economy as opposed to being thrown away as waste, supporting environmental preservation and sustainability objectives.

10. Education and training

The need for education and training in promoting knowledge and comprehension of material passports (DMP) was emphasized by the participants, especially in places like Saudi Arabia and Pakistan where physical passports may not be well known (SD2). It is believed that dispelling any misunderstandings regarding the objectives and benefits ofMP is essential to overcome popular opposition (SD2). Participants stressed the need of training building professionals, such as architects, engineers, and contractors, as major stakeholders in adopting MP, in addition to raising public awareness (SD2). Programmes for education and training might lead these specialists through the manufacture and upkeep of DMP and provide them with information about their possible advantages and disadvantages (SD2). One anticipated consequence of this is the incorporation of MP into building projects with the intention of fostering sustainability, transparency, and circularity.

Participants also suggested that workshops, online courses, and industry conferences are just a few of the different ways that education and training may be provided. Depending on the target demographic and the extent of the training, they proposed that these programmes may be organized by governmental organizations, business groupings, or academic institutions. Participants concluded that material passport education and training might be a major factor in boosting the uptake and application of this cutting-edge technology in the construction sector.

11. Awareness and understanding

A critical component (node SR1) of the conversations was participants' awareness and knowledge of digital material passports (DMPs), with most exhibiting a basic grasp of the idea and its importance. It was observed, meanwhile, that a small percentage of participants—mostly Saudi Arabians—held false beliefs regarding the objectives of DMP. While some participants mistakenly thought that DMP were mainly useful for major building projects, others saw their primary use as material source monitoring, rather than thoroughly addressing the composition and qualities of the materials.

Most participants considered their comprehension of the material passport idea to be adequate, despite a small percentage holding these misunderstandings. This reaffirms the necessity of focused awareness campaigns, particularly in areas such as Saudi Arabia, in order to confront and clear up any misunderstandings and guarantee a thorough comprehension of the many functions and advantages that DMPs provide to the building industry. By debunking misconceptions and promoting a nuanced understanding among stakeholders, education and awareness initiatives may be crucial in improving the adoption of DMP.

12. Overall opinion on DMP and incorporation

Emphasis is placed on the digital material passport (DMP) (OP1)'s inevitable role in forming the future circular economy in the construction industry. While there is a chance that DMP may be included into larger databases, the basic idea is still the same: making sure that DMP or, at the absolute least, detailed information for every material and component, are readily available. This emphasizes how important it is for DMP to help with the effective reuse of components and materials (B1, B3, D1), which is in line with the fundamentals of sustainability and circular building practices.

13. Suggestion and recommendation for successful implementation of DMP

It takes a variety of tactics to properly implement a digital material passport (DMP). Providing incentives, such tax rebates, can encourage people and businesses to use DMP in their building processes (SR1). To guarantee that the data in DMP is consistent and simple for all stakeholders to grasp, standardization activities are essential (SD1). To ensure the safety and compliance of repurposed materials, quality assurance via standard testing and compliance processes is required (KR1). By providing a useful forum for bringing together potential providers and those in need, the creation of materials exchanges helps advance the circular economy (SD1). Investigating novel business strategies that complementMP, such as service-based models, has the potential to transform the construction sector and promote progress (B1). Effective approaches to valuation and measurement require industry collaboration in research.

The topics that were taken from the interviews offer a thorough understanding of the requirements, advantages, and difficulties related to the deployment of digital material passports (DMP) from a variety of angles. The general topic of "Challenges in digital material passport implementation" (C1 to C2) encompasses both cultural and technological obstacles, such as the requirement for machine-readable, standardized material. Alongside these difficulties, there are also insights into the possible advantages for businesses (B1 to B3), which emphasize the rise of new business models and the function of DMPs in calculating and lowering carbon footprints. The necessity of "Design for Disassembly" is emphasized by the engagement of designers (D1 to D2), while the involvement of construction firms (CF1 to CF2) highlights the need for a new standardization and testing regime.

The worldwide perspective provided by the topic "Usage of material passports in the Industry and Country" (U1 to U2) illuminates the differing levels of adoption in Saudi Arabia, Pakistan, Estonia, and Australia. The primary needs for successful implementation

(KR1 to KR5), which highlight the need of standardization, incentives for material reuse, and efficient material exchanges, are reflective of this variety. Material components and maintenance needs are only a couple of the topics covered in DMP (I1 to I2), which emphasizes the importance of having comprehensive and current documentation. It is acknowledged that standardization and digitalization (SD1 to SD3) are essential steps in the implementation process that guarantee the functionality and compatibility of digital MP.

The consensus on DMP (OP1 to OP2) is that they will inevitably play a role in the building industry's circular economy in the future. For an DMP implementation to be effective, the recommendations and proposals (SR1 to SR2) reiterate the significance of incentives, standardization, and cooperative research. This interwoven story, which integrates technological, cultural, and international factors, highlights the complex nature of Material passport implementation.

4.4 Discussion of results

Analyzing Digital Material Passports' (DMPs') ability to propel the circular economy in the built environment reveals a complex world with many ramifications and difficulties. This examination, which is based on qualitative research and is enhanced by interviews with important industry players, provides a thorough analysis of the consequences of DMP adoption by combining knowledge from a variety of academic sources and previous studies. By delving deeper into the results and providing connections to earlier research and conversations on relevant subjects, this section builds on the concepts introduced in the literature review.

Stakeholder interviews consistently highlight the disruptive potential of DMPs, establishing them as key components in transforming the construction industry's approaches to sustainable building materials. These observations are consistent with past research showing how DMPs can improve material consumption efficiencies and reshape paradigms for resource management (Jensen et al., 2023). Furthermore, the interviews underscore the crucial function of standardization and digitization in guaranteeing the operational efficacy of DMPs, conforming to the findings made by academics like Honic et al. (2019). Important themes that keep coming up include the pressing need for machine-readable, standardized DMP materials and smooth interface with different software systems, which are in line with previous research's imperatives (Cetin et al., 2022).

The complex technical environment that surrounds DMPs emphasizes how urgently standardization and digitization are needed. This confirms the results of other studies, highlighting the necessity of machine-readable, standardized DMP content and

interoperability with various software systems to guarantee their efficient operation.(Byers and De Wolf, 2023).
The construction sector needs to undergo a fundamental shift in mindset before DMPs can be broadly implemented. Buildings as "banks" or archives of materials challenges conventional wisdom and necessitates a dynamic re-evaluation of the built environment. This is in line with studies that advocate for the building sector to embrace a circularity paradigm that integrates with the Sustainable Design Goals and the Circular Economy.

How to integrate DMPs with the objectives of the circular economy and sustainable design principles is one of the primary conversation topics. Prior studies shed light on the ways in which DMPs facilitate effective material reuse, particularly about concepts such as Design for Disassembly (DfD). This, in turn, encourages congruence between the goals of the circular economy and sustainable design methodologies (Jensen et al., 2023). Beyond technical issues, the interviews made clear that the construction industry needs a fundamental paradigm change, with stakeholders being pushed to reconsider buildings as dynamic repositories of material. Atta (2021) argues that this paradigm-shifting move aligns with the principles of the circular economy and defines DMPs as fundamental components of frameworks for sustainable design and the circular economy. According to Sanchez et al. (2024), the interviews also demonstrate the ways in which DMPs and Design for DisassemDMPs,(DfD) principles can complement one another, underscoring the role that DMPs play in promoting sustainable design methodologies.

Though the future seems bright, DMP adoption is still not uniform worldwide, with clear regional differences in attitudes and readiness for implementation. This emphasizes the need for educational programs that aim to improve awareness and capacity-building for successful DMP adoption, as stressed by Vahidi et al. (2023). As the interviews made clear, these kinds of efforts are essential for filling in knowledge gaps and creating an atmosphere that is favorable to the implementation of DMPs

Despite the promising prospects of DMPs, acceptance is still slow worldwide, with regional differences in acceptability being noted. The need of education for successful implementation is highlighted, reiterating findings from earlier research that highlight the necessity of extensive information distribution and capacity-building initiatives to support the widespread adoption of DMPs.

The overall conclusions drawn from the interviews highlight the critical role that DMPs play as vital components of sustainable construction techniques used all over the world. DMPs are presented as transformative instruments that are accelerating the shift to a more sustainable and circular built environment, in line with earlier research.

5 CONCLUSIONS

Examining how digital material passports (DMPs) might support a circular economy in the built environment has provided important insights into the prospects, challenges, and transforming possibilities facing the construction sector. An outline of the thesis, important conclusions, their ramifications, and potential directions for future study and real-world applications are given in this part. The expedition commenced with precisely delineated goals: investigating the potential of DMPs, comprehending the obstacles linked to their implementation, and projecting their function in propelling a circular economy. These goals provided as the foundation for research and well-informed conversations with a wide variety of construction industry stakeholders. Finding the obstacles preventing the smooth deployment of DMPs turned out to be one of the journey's most important discoveries. These challenges highlight how difficult it is to implement cutting-edge tactics like DMPs, from the requirement for standardization to the necessary cultural changes inside the construction industry.

The study's investigation uncovered the strong benefits that DMPs provide to companies. DMPs have the power to completely change the way that firms operate, from cutting-edge business models to carbon footprint reduction tactics. The study looked at the crucial roles that designers, contractors, and construction businesses had in promoting the use of DMPs. Gaining a general understanding of their contributions is essential to promoting DMP adoption and use.It was discovered that DMPs are primarily in Estonia's experimental stage now. Different nations display differing degrees of acceptance and assimilation, as demonstrated by the situations in Australia, Saudi Arabia, Pakistan, and the Philippines.

5.1 Key findings

The implementation and impact of DMP was found to have several dimensions, as indicated by the examination of interviews conducted with a range of stakeholders, including construction companies, designers, and industry experts. The difficulties include both technological and cultural components, highlighting the requirement for machine-readable, uniform, and broadly applicable DMP (C1, C2). Since construction companies are at the forefront of material reuse, standards, testing, and quality control procedures need to change dramatically (CF1). "Design for Disassembly" (DfD) is a topic that designers are extremely interested in, which emphasizes how important sustainable design principles are to creating a circular built environment.

1. **Environmental benefits**

DMP has the ability to minimize greenhouse gas emissions, cut waste, and reduce energy usage, all of which have a substantial positive impact on the environment (EBB). The adherence of DMP to the principles of the circular economy promotes environmentally conscious economic practices and responsible material usage (EBB).

2. **Global perspective for implementation of DMP**

The research acknowledged the variation in DMP uptake and integration around the globe. Other nations, such as Australia, Saudi Arabia, and Pakistan, show varying degrees of adoption and implementation, while Estonia is still in the experimental stages (U1, U2). This worldwide variance emphasizes the necessity of customized strategies in various situations.

5.2 Future implications and recommendations

The study's findings position DMPs as major participants in the construction industry's shift to a more sustainable and circular future by highlighting their revolutionary potential as global catalysts for sustainable construction practices. When used as change agents, DMPs can open the door to a future where the built environment is more circular and sustainable, following the path previously set by research. Through qualitative research and stakeholder interaction, this work advances our understanding of the mechanisms and challenges associated with DMP adoption, paving the way for targeted interventions and well-informed decision-making to advance sustainable construction practices.

The focus of future research should be on addressing the identified barriers, developing improved awareness, and developing feasible strategies for global implementation. The need for international cooperation and information exchange is made clear in this setting.

In conclusion, the process of introducing digital material passports into the built environment has made clear the challenges as well as the opportunities that they present. Embracing a circular economy, incorporating recycled materials, and enacting the required cultural shifts are some challenging but achievable challenges. To realize our goal of a more sustainable building industry, DMP is crucial. A sophisticated and situation-specific strategy is required to adopt the various opinions that stakeholders have voiced.

The findings of this study add to the growing body of knowledge about DMP and set the foundation for further research. DMP serves as a beacon, guiding the construction sector toward a future in which materials are appreciated, recycled, and the built environment places sustainability at the center as it works through the complexities of a circular economy.

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