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REVIEW ARTICLE

Transformation of the automotive industry: A systematic literature review on the technological drivers of transformation

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Abstract

The automotive industry is undergoing a profound transformation driven by technological innovations, such as electrification, autonomous driving systems, digitalization, and the shift toward mobility services. This transformation is further intensified by new competition from the IT sector, industrial policy objectives, particularly from China, and the increasing automation and connectivity of manufacturing processes. In addition, environmental regulations, evolving consumer preferences, and advancements in artificial intelligence (AI) play a crucial role in shaping the industry's future. This study aims to identify and analyze the key technological drivers contributing to the transformation of the automotive sector. Using a systematic literature review based on the approach outlined by vom Brocke *et al*., a structured and reproducible analysis of the relevant literature is conducted. The findings indicate that technological drivers, such as connectivity, autonomous driving, electrification, and digitalization are crucial to this transformation. Furthermore, supporting technologies such as AI, cloud computing, and big data analytics are critical enablers of this transformation. A deep understanding of these drivers is essential for industry stakeholders, policymakers, and researchers to anticipate future developments, address emerging challenges and develop effective strategies for sustainable and competitive mobility solutions. This study contributes to the ongoing discourse on transformation and its implications for the future of the automotive industry.

Keywords: Automotive industry; Transformation; Technological drivers

1. Introduction

Mobility, transportation, and logistics are fundamental to modern society and are currently undergoing a paradigm shift that presents both opportunities and challenges. At the center of this development is the global automotive industry, including established leaders such as Germany, Japan, the U.S., and France, as well as emerging players, such as China, which is rapidly expanding its influence. The transformation in this industry is influenced by a variety of factors, particularly the increasing electrification, the development of autonomous driving systems, and the shift toward mobility services.[1] In addition, rising competition from the IT sector and industrial policy objectives – especially from China – is accelerating this shift and reshaping the future of mobility, transportation, and logistics. Furthermore, the ongoing automation and connectivity of manufacturing processes are profoundly impacting value-creation networks, with significant implications for Germany's industrial landscape.[2] While economic dynamics and regulatory frameworks influence the pace and trajectory of this transformation, technological innovations contribute significantly to driving fundamental shifts within the industry.[3] In particular, advancements in electrification, autonomous driving, connectivity, and artificial intelligence (AI) are expected to be key drivers of this transformation. These technologies not only redefine vehicle design and manufacturing processes but also influence emerging business models and regulatory frameworks.[3] Therefore, it is crucial to identify the technologies that will dominate the automotive sector in the future to thoroughly analyze the consequences of this shift and its impacts.[4]

The present study aims to identify the technological drivers that significantly contribute to the transformation in the automotive industry. A deep understanding of these advancements is essential to accurately assess the challenges and opportunities of the transformation process, to anticipate potential developments for industry, policy, and society and to develop appropriate strategies and frameworks that promote sustainable and future-oriented mobility.

The central research question is: "Which technological drivers are significantly shaping the transformation in the automotive industry?" To answer this question, this study utilizes a systematic literature review following the approach outlined by vom Brocke *et al.*,[5] which enables a structured and reproducible analysis. This paper is structured as follows: Following this introduction, Section 2 explains the theoretical framework concerning the transformation and its drivers. Section 3 describes the research methodology, detailing the systematic literature review approach used in this study. The results of the literature review are then presented in Section 4. In Section 5, a conclusion is drawn, with limitations discussed and an outlook provided.

2. Theoretical background

2.1. Transformation, transition, and structural change

Understanding the transformation of the automotive industry requires a theoretical foundation that distinguishes between different types of systemic change. The terms transformation, transition, and structural change are frequently used in both academic and policy discussions to describe fundamental shifts in industries, economies, and societies. However, their precise meanings and implications vary depending on the context. This section provides an overview of these concepts and highlights their relevance to the ongoing transformation of the automotive industry.

Transformation is a comprehensive term used in various academic disciplines, such as mathematics, electrical engineering, biology, as well as the economic, social and cultural sciences.[6] These different perspectives highlight the complexity and diversity of transformation processes by emphasizing various aspects such as the objects of transformation, the pace, and the necessary means to initiate these processes of change.[7] Transformation processes can occur both in limited systems at a short to medium-term level, for example, through technological innovations or changes in business models and at a long-term, overall societal level.[7]

In the business context, transformation at the micro level is defined as a targeted process of realigning organizational resources and capabilities to move from an existing state to a defined target state. The term is particularly used in the context of reorganizing business processes and business models.[8] For instance, automakers are redefining their business strategies to integrate software-driven mobility solutions. At the macro level, Wittmayer and Hölscher[9] describe transformation as structural, radical, and paradigmatic changes in societies and their subsystems. These changes lead to a fundamental redesign of a system's functional objectives and their implementation. This process can involve the coexistence of old and new elements, such as disruptive technologies or new industries.[7]

In political and academic discourses, the terms "transition" and "transformation" have become key concepts that are often used interchangeably to describe profound processes of change in complex adaptive systems.[10] Transition refers to technology-influenced processes of change in socioeconomic systems, including system innovations and functional transformations in socioeconomic fields. The term is particularly used in sustainability research to describe profound changes in social, technological, institutional, and economic structures.[9,10] Transition focuses on institutional and political changes within sociotechnical and socioeconomic systems and analyzes changes in societal subsystems.[9,10] In contrast, transformation describes an extensive process of change that involves widespread alterations across entire societies at global, national, and local levels. This distinction shows that transition covers specific, often technically oriented aspects, while transformation encompasses broader social, technological, institutional, and economic changes.[9,10] For the purposes of this work, the term "transformation" is used, as it more comprehensively covers these profound changes.

In addition to the term "transition," the term "structural change" is frequently used in the context of transformation. Structural change refers to the ongoing alteration of the economic structure, where the significance of individual sectors shifts over time.[11] While traditionally described as a shift from the primary to the secondary and then to the tertiary sector,[11] modern economies exhibit more complex interdependencies. The increasing importance of knowledge-based services, research and development (R&D), and digitalization has led to the emergence of a quaternary sector, which encompasses high-value services such as consulting, IT, and advanced producer services that support industrial activities. These structural shifts influence both the manufacturing sector and service-based industries, as technological advancements and evolving market demands create new dynamics between sectors.[12] When the focus of a transformation process is on the economic system of a state, the concepts of transformation and structural change can largely be considered synonymous.[7] Structural change can occur in three dimensions:

Sectoral structural change: Long-term changes within the sectoral economic structure due to varying growth rates of individual sectors.[13]

Intra-sectoral structural change: Changes within individual sectors caused by product innovations or changes in production technology.[13]

Regional structural change: Changes in the economic structures within regional economic areas, influenced by specific location factors that determine the direction and extent of the change.[13]

In the context of the automotive industry, the transition from internal combustion engines to electrified propulsion systems, combined with the growing relevance of digital mobility services and automation, exemplifies structural change within and across sectors.[13] The development and deployment of new mobility concepts increasingly rely on advancements in digital infrastructure, software integration, and R&D, highlighting the role of knowledge-intensive services in shaping industrial transformation.[12]

2.2. Types of change

In the scientific literature, two main types of change are distinguished: Evolutionary and revolutionary change, which can be classified as first-order or second-order change depending on their depth and scope.[14] First-order change is evolutionary and involves incremental adjustments within existing systemic boundaries, without fundamental reshaping of the organizational culture, strategic direction, behavioral standards, processes, or structures. These changes are quantitative, evolutionary, and limited to specific units or segments of the organization, with limited intensity and complexity.[15]

Second-order change is revolutionary and transformative, affecting the entire organization or significant segments of it, leading to fundamental, profound, and complex changes.[15] These changes represent a qualitative, paradigmatic development of the company and its frame of reference.[14]

Wayland[16] expands this view by considering the influence of industry structure and the external environment, distinguishing four types of change: Incremental, contextual, structural, and fundamental change.

2.3. Technology-induced transformation

Technology-induced transformation represents a paradigm shift, where technological innovations bring about fundamental changes.[17] Schumpeter[18] describes this process as creative destruction, in which existing structures are replaced and new ones are created. Numerous theories and models have been developed in the scientific literature to explain technology-induced changes.[19-22] This work employs Foster's S-curve model and Christensen's theory of disruptive innovation, as they provide fundamental insights into the dynamics of the automotive industry.

The S-curve model, based on Arthur D. Little's technology life cycle, describes the life cycle of technologies from the emergence phase through growth to maturity and finally to the phase of aging or decline.[23] The model illustrates the performance of an established technology and its substitute technology, shown in relation to the cumulative effort in R&D.[24] This relationship is depicted by the slope of the curve, which symbolizes the performance gain relative to the R&D effort expended, thus reflecting the productivity of R&D.[24] It demonstrates that technological developments have inherent limits and shows that initially high investments in new technologies are required before they reach a turning point, after which comparatively low additional investments lead to significant performance improvements.[23] Foster extends this concept with the theory of technological discontinuity, which explains why new technologies are initially inferior and why established companies are hesitant to invest in them. New market entrants, unburdened by legacy issues, can leverage these technologies to surpass established companies.[21]

Christensen's theory of disruptive innovation builds on the S-curve model and distinguishes between disruptive and sustaining technologies. Disruptive technologies often start in niche markets and may initially not offer the same performance as existing technologies from the customer's perspective. However, they create new customer value through technical advancement and ease of use, eventually displacing established technologies. Sustaining technologies optimize existing products by improving performance based on consumer preferences. The Innovator's Dilemma describes the challenge company's face in balancing the focus on present customer demands with timely engagement in disruptive technologies, which often leads to faster technological advancement than the development of market needs.[24]

2.4. Drivers of transformation

In the literature, the term "drivers of change" is used to characterize factors that stimulate or necessitate change processes within corporate structures.[25] Wiendahl[26] defines them as external and internal influences and impulses that can trigger changes. Westkämper[27] refers to them as turbulences and also distinguishes between external and internal influencing factors. Nyhuis describes drivers of change as a multitude of overlapping and mutually influencing factors that together create a turbulent environment and generate pressure for change at various system levels.[28] Synonyms such as transformation drivers[29] and transformation triggers[30,31] are also used to characterize these influencing factors. It is crucial that companies are able to control the impacts of dynamic influencing factors and leverage them to increase their efficiency.[25] The ability to adapt to continuously changing environmental demands is thus essential for the long-term viability of companies.[25]

The corporate environment, especially in the automotive industry, is characterized by turbulence due to the dynamics in surrounding markets, rapid technological developments, and fluctuations in available resources.[25,32] Turbulence in the automotive industry, for example, manifests through resource shortages. The lack of semiconductor products limits the production of important preliminary and intermediate products and is thus considered a constraining factor for automotive production.[33] In this context, the ability to adapt and change are crucial success factors for companies in global markets. The continuous change in influencing factors constantly creates new circumstances to which companies must adaptively respond. The critical component lies in balancing adaptability and robustness to successfully operate and promote growth under dynamic influences.[25]

In this context, the literature distinguishes between internal and external drivers.[25,34] Internal drivers of change develop through the transformation of a company's capabilities, internal structure, and resources. In contrast, external drivers are market- and field-driven and arise from environmental turbulence.[25,32] External causes include economic, technological, and political-legal aspects. Economic drivers of change involve shifts in customer behavior, the competitive landscape, and labor and financial markets, including the trend toward customer-specific and personalized products.[25,32] Technological drivers refer to the introduction of innovative technologies or significant technological advancements that impact production processes.[32] Political-legal factors encompass changes in political and regulatory frameworks, such as binding agreements between trade unions and companies.[25,32]

Internal corporate developments, such as fluctuating order volumes, changes in personnel structure, or the introduction of new technologies, also require flexible adaptability. Internal drivers have significant impacts on aspects of the company such as products, competencies, resources, and organizational structure.[32] The introduction of new product variants and changes in the order situation can lead to adjustment processes. Changes in organizational structure and operational resources, such as equipment, capacities, infrastructure, and personnel, are also significant internal influences. In addition, adjustments to internal capabilities may be necessary. These can involve changes within the personnel structure, corporate culture, or technology portfolio, thus acting as catalysts for internal change processes.[32]

It is evident that influencing factors are interconnected and their effects become significant only through changes within the system. Consequently, conceptual and structural measures can be derived from the insights gained from these drivers.[25]

This publication focuses on the technological drivers of change. In their book *Excellence in Change*, Krüger and Bach[34] demonstrate that technological drivers are among the most important external influencing factors, highlighting the relevance of examining them.

3. Materials and methods

In this paper, the framework by vom Brocke *et al.*[5] is used as the methodological basis for the study. The model begins with the first phase, defining the scope of the literature review. vom Brocke *et al.* utilize the taxonomy developed by Cooper[35] to classify literature reviews. This classification is based on six characteristics: Focus, goal, perspective, coverage, organization, and audience, which can vary in different ways.[35] This literature review focuses on research findings concerning the technological drivers of change. The primary aim of this publication is to summarize the existing literature. A neutral, representative perspective was consistently adopted for the literature search and analysis to provide an objective overview of the literature. The scope of the review is characterized as selective, meaning that after an exhaustive search, the focus was narrowed to the most essential content. In addition, a conceptual framework was chosen for this work. The paper is intended for the general public. Figure 1 illustrates Cooper's described taxonomy, with the highlighted fields corresponding to the chosen framework for the present paper.

Based on the relevant literature presented in the second section, which forms the theoretical framework of this work, key terms, as well as their synonyms and related terms, were identified. A concept map was then created to structure the topic area. The literature search was conducted using a constructed search string and various online databases, such as Sage Journals, ScienceDirect, SpringerLink, Taylor & Francis Online, and Emerald Insight. The search strings were tailored to each database to account for their specific search formats. Inclusion and exclusion criteria were established for the search process. Literature published before 2014 and non-German or non-English publications were excluded. Literature focusing on the markets of Europe, North America, and East Asia was included. The quality of the academic journals was ensured using the VHB-Jourqual Ranking[36] (2015), with only journals rated C, B, A, and A+ being included. In addition, criteria such as an H-index of at least 25 and an impact factor of at least 2 were considered. The search was limited to the period from 2014 to 2024 and focused on titles and abstracts to optimize the number of relevant results. The keywords were used in English, based on insights from the VHB-Jourqual Ranking search. A total of 18 relevant sources were identified, and after checking for duplicates, 11 essential sources were selected to answer the research question. To ensure transparency in the literature selection process, a PRISMA flow diagram (Figure 2) is provided below. It illustrates the different phases of identification, screening, eligibility, and inclusion, offering a structured overview of how the final set of sources was determined.

4. Results of the literature review

To assess the technological drivers shaping the transformation of the automotive industry, a systematic literature review was conducted. A total of eleven relevant publications were analyzed. ScienceDirect proved to be the primary database with five relevant sources, followed by SpringerLink and Taylor & Francis Online with two hits each. Sage Journals and Emerald Insight each provided one relevant source.

The publication years of the selected works range from 2016 to 2023, with at least one relevant publication each year, except for 2018 and 2019. Notably, five significant studies were added in 2023, highlighting the growing relevance of the topic. In terms of media types, the examined works consist of nine journal articles, one book chapter, and one conference paper.

For a detailed analysis of the researched literature regarding its contents, the concept matrix method proposed by vom Brocke *et al.* is applied. This method assigns the contents to various technological influencing

Characteristics		Categories			
1	Focus	Research outcomes	Research methods	Theories	Applications
2	Goal	Integration	Criticism	Central Issues	
3	Perspective	Neutral representation		Espousal of position	
4	Coverage	Exhaustive	Exhaustive and selective	Representative	Central / pivotal
5	Organization	Historical	Conceptual	Methodical	
6	Audience	Specialized scholars	General scholars	Practitioners	General public

Figure 1. The taxonomy of the literature review according to vom Brocke *et al.*[5]

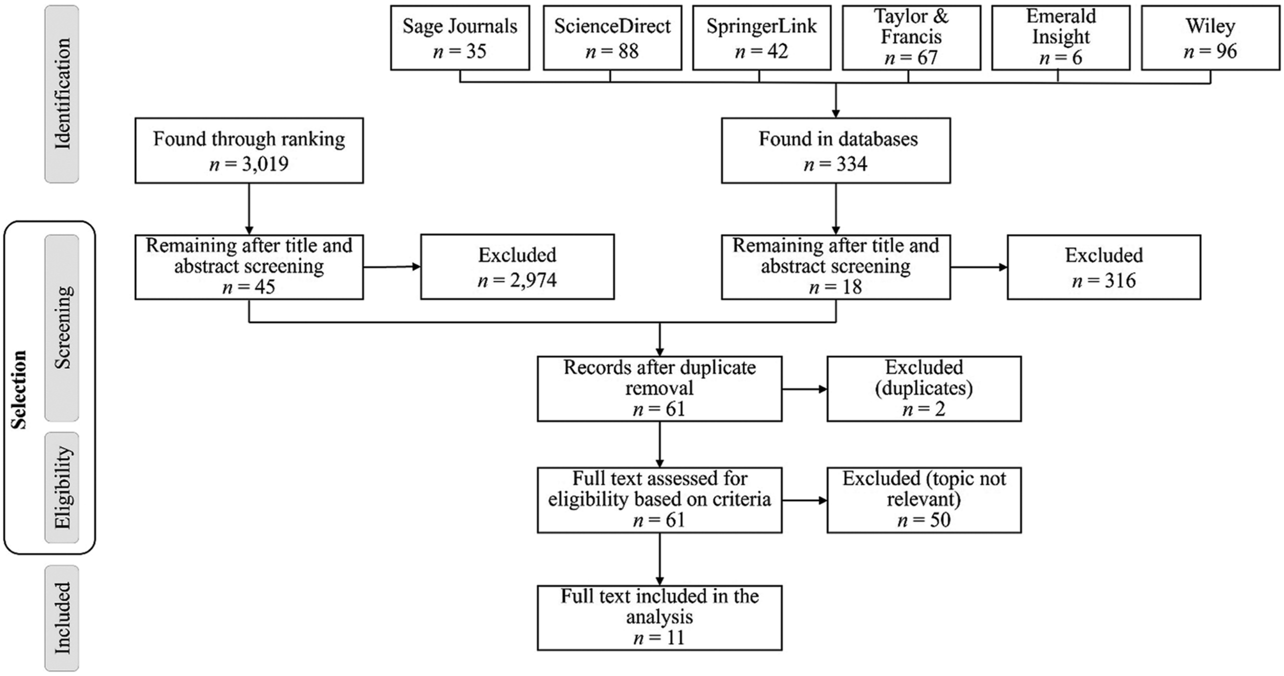

Figure 2. PRISMA flow chart

factors and serves to systematically capture and compare these contents, facilitating an understanding of the present state of research. The concept matrix helps identify research gaps by highlighting which areas have already been extensively studied and where further research is needed. A complete visualization of the concept matrix can be found in Table A1 (in Appendix), while a selected excerpt is presented in Table 1. This overview provides a solid foundation for the subsequent deeper qualitative analysis, which will be initiated and expanded in the next chapter.

The technological drivers identified in the literature review were connectivity, autonomous driving, electrification and alternative drive technologies, as well as digitalization. In addition to the primary drivers, supporting technologies were also identified but not examined in detail. These include AI, digital platforms, big data, robotics, 3D printing, and cloud computing. The concept matrix provides a structured overview of the distribution of these technological drivers across the analyzed literature. It systematically maps which sources discuss specific technological factors, highlighting the prevalence and emphasis of each driver within the existing research.

4.1. Connectivity

Connected and autonomous vehicles (CAV) have the potential to transform business models, according to Turienzo *et al.*[38] Hoeft[37] identifies vehicle connectivity as a central enabler of other CASE dimensions (Connected, Autonomous, Shared, and Electric) and emphasizes the opportunity to create economic, social, and ecological value. Connectivity facilitates communication between various systems both within the vehicle and with external systems. Connectivity can be categorized into vehicle-to-everything, vehicle-to-vehicle and vehicle-to-infrastructure.[44]

Connectivity allows automotive manufacturers access to large datasets to improve customer experience and product quality. Individual user profiles contribute to the personalization of the driving experience, for example, through integration with systems, such as Apple CarPlay and Android Auto.[37]

Kuang[44] describes that intelligent connected vehicles change the product forms and service patterns of the traditional automotive industry, leading to a fundamental shift in the value chain. In product design and development, this results in changes to the structure, components, and appearance of vehicles, such as replacing traditional actuators with mechatronic systems. The industrial organization in production is expected to undergo intense transformation, as product value shifts from automobiles to relevant data and services, potentially reducing the dominance of original equipment manufacturers (OEMs). In the era of intelligent connected vehicles, the structure of the automotive industry will fundamentally change.

Table 1. Literature analysis and synthesis through the concept matrix – excerpt

Author	Title	Technological drivers				Supporting technologies						
		Connectivity	Autonomous driving	Electrification	Digitalization	Alternative drive technologies	Artificial intelligence	(Digital) platforms	Big data	Robotics	3D printing	Cloud computing
Hoeft[37]	Assessing dynamic capabilities of incumbents in the face of unprecedented industry transformation: the case of the automotive industry	X	X	X			X					
Turienzo *et al.*[38]	Business models in times of disruption: The connected and autonomous vehicles (uncertain) domino effect	X	X		X		X	X	X			
Yeung[39]	Competitive dynamics of lead firms and their systems suppliers in the automotive industry		X	X	X							
Grimm & Walz[40]	Present and future roles of the automotive and information and communication technology sectoral systems in autonomous driving – Using the innovation system approach to assess value chain transformation		X									
Lopez-Vega & Moodysson[41]	Digital Transformation of the Automotive Industry: An Integrating Framework to Analyze Technological Novelty and Breadth	X	X	X	X		X			X		X
Ferràs-Hernández *et al.*[42]	Disruption in the automotive industry: A Cambrian moment	X	X	X				X	X		X	

(Cont'd...)

Table 1. *(Continued)*

Author	Title	Technological drivers				Supporting technologies						
		Connectivity	Autonomous driving	Electrification	Digitalization	Alternative drive technologies	Artificial intelligence	(Digital) platforms	Big data	Robotics	3D printing	Cloud computing
Wittmann[43]	Electrification and Digitalization as Disruptive Trends: New Perspectives for the Automotive Industry?	X	X	X	X				X			X
Ziegler & Abdelkafi[4]	Exploring the automotive transition: A technological and business model perspective	X	X	X		X						
Kuang *et al.*[44]	Intelligent connected vehicles: the industrial practices and impacts on automotive value-chains in China	X	X				X	X				
Frieske & Stieler[45]	Resilient Supply Chains and Robust Strategies for the Transformation of the Automotive Industry		X	X	X			X				
Llopis-Albert *et al.*[46]	Impact of digital transformation on the automotive industry				X							

Note: In the concept matrix by Webster and Watson, the cross "X" in the shaded box indicates that the article makes a significant contribution to a key driver of the transformation in the automotive industry, whereas the "X" on a clear background signifies that the driver is mentioned but not a primary focus of the article.

The industry will evolve into a multi-cooperation eco-network where manufacturers (OEMs) no longer function solely as integrators of automobile products but also as providers with specialized integration capabilities, actively participating in this connected ecosystem.[44]

Established automotive companies face the challenge of adapting their ecosystems and partnerships to meet the new demands for dynamic capabilities. Particularly, the need for regular software updates presents a significant challenge, as they enable continuous improvements in vehicle usability but also require advanced IT architecture competencies within the vehicle. This development forces traditional automakers to rethink and expand their technical capabilities and willingness to cooperate to remain competitive in an increasingly digital and connected market environment.[37]

4.2. Autonomous driving

Autonomous driving is a key technology in the transformation of the automotive industry, characterized by vehicles operating with minimal or no human intervention. Essential components include sensors, such as Lidar and GPS, advanced data interpretation software, technical infrastructure for computing capacity, and precise steering systems.[37] The development and implementation of autonomous vehicles require the integration of various technologies and disciplines, making the field highly competitive and resource-intensive.[40]

The introduction of CAV depends on technological advancements and the development of appropriate concepts for mobility services. This development enables companies from various industries, including high-tech firms, telecommunications companies, IT corporations, venture capitalists, data management companies, and energy providers, to realize innovative business models and ideas. Continuous data analysis optimizes these services and enhances the overall business environment.[38,40]

The increasing automation through autonomous vehicles brings significant digital innovations with the potential to fundamentally optimize business models. According to Turienzo *et al.*, these developments are driven by a variety of players, including start-ups, spin-offs, subsidiaries of established companies, and new entrants from the information and communication technology (ICT) sector.[37,38] The market for motorized private vehicles faces new challenges from companies in the ICT sector.[40]

The findings of the study by Grimm and Walz[40] suggest that automotive manufacturers primarily focus on developing autonomous vehicles and their technological components, while ICT companies concentrate on creating digital environments and solutions. Both sectors are involved in mobility services, with automotive companies primarily providing hardware and ICT firms offering platform services. Despite some overlaps in technology and services, a complementary collaboration is emerging, especially in the development of software and hardware components.[40]

Specified system suppliers and other relevant actors could be better positioned than established automotive manufacturers to benefit from the transformation. According to Yeung,[39] integrating semiconductor control modules, electronic components, and safety features requires a complex structure, regardless of whether vehicles are shared or autonomously operated. System suppliers with the necessary technological competencies for autonomous driving not only show increased resilience to emerging megatrends but are also in a favorable position to consolidate or even expand their competitive advantages. Thus, these actors could potentially become leading companies within the newly structured automotive value chain.[39]

Moreover, the increased capacity utilization of autonomous vehicles could lead to a reduction in the number of vehicles, presenting challenges for OEMs and suppliers.[37]

4.3. Electrification

Electrification in the automotive industry marks a paradigmatic shift from internal combustion engines to electric drives, driven by stricter emission controls and increasing environmental awareness. This development has accelerated the adoption of advanced microelectronics and battery technologies by automakers, altering competitive dynamics, particularly with respect to system suppliers.[37,39] Yeung[39] describes that electric drives have significantly fewer wear parts than traditional internal combustion engines, impacting not only the complexity and maintenance of vehicles but also the supplier industry, especially manufacturers of standardized components and those specializing in internal combustion engine technology. Traditional suppliers manufacturing components for electrical or electronic systems must adapt their products to new processors to remain competitive. This could geographically shift value chains, particularly to Asia, where the market for electric vehicles is growing.[39]

Various propulsion technologies, such as battery electric vehicles and fuel cell electric vehicles, are competing for dominance, with infrastructure availability playing a crucial role. Ziegler & Abdelkafi's study[4] concluded that experts predict a coexistence of both technologies, with fuel cells being particularly advantageous for heavy loads and long distances and battery vehicles for passenger transport over shorter distances.

4.4. Digitalization

Digitalization in the automotive industry marks a significant shift through the introduction of digital technologies, driven by data management and digital platforms. These technologies have the potential to revolutionize traditional business models and create new market offerings through big data and AI.[38] The ability to efficiently manage data and transform it into actionable knowledge has become crucial in customer management and sales.[38]

Digital technologies accelerate industrial transformation, leading to the emergence of new players and potentially reconfiguring industrial value chains. The automotive industry is opening its value chains to digital experts with experience in electronics and software, enabling new cooperative business models based on digital platforms and big data.[41,42]

The development of information and communication technologies has led to the digitalization of vehicles and the definition of topics such as connected cars, the Internet of Things, and autonomous driving. These technologies provide insights into customer behavior and market demands, which can be used to create new products and services.[43]

The changes brought about by digitalization and electrification require agile approaches to delivering digital solutions to effectively manage the disruptive nature of these technologies and adapt traditional business models to meet the new demands.[38]

5. Conclusion, limitations, and outlook

5.1. Conclusion

As part of the systematic literature review, the research question "Which technological drivers significantly shape the transformation in the automotive industry?" was investigated. The aim of the study was to identify the key technological drivers currently influencing the transformation through a systematic literature review. To identify the relevant sources for this study, a keyword search was conducted across various databases, resulting in 11 relevant sources. The analysis of the selected publications identified several technological factors that are crucial to the transformation in the automotive industry. The primary drivers of this change are connectivity, autonomous driving, electrification and digitalization. These main drivers are supported by complementary technologies such as AI, digital platforms, big data, robotics, 3D printing, and cloud computing. The investigation revealed that these drivers interact with each other and are often discussed in combination in the literature. For companies, it is essential to gain a deep understanding of these key technologies to analyze the impact of the transformation and respond appropriately. A comprehensive understanding of these technological developments is essential to accurately evaluate the challenges and opportunities of the transformation process and to develop suitable strategies.

5.2. Limitations

Although this research offers valuable insights, it is important to recognize certain limitations:

(a) *Methodological approach.* The systematic analysis of existing literature inherently involves certain limitations. The results can be influenced by the chosen search strategy, inclusion and exclusion criteria, as well as the reviewer's personal perspectives. Despite the methodological frameworks outlined by vom Brocke *et al.*, the risk of reviewer bias remains, as the selection and interpretation of literature are subjectively influenced.

(b) *Language limitations.* Focusing on English-language literature may exclude relevant research findings available in other languages. To minimize the potential impacts of this language limitation on the research outcomes, it is advisable for future research to include relevant sources available in other languages, thereby providing a more comprehensive view of the state of the art.

(c) *Access to databases.* The limitation of the literature search to databases accessible through university licenses or those that are freely available also presents a methodological constraint. Although a well-founded selection of databases was made using journal rankings, relevant publications in databases not considered may have been overlooked. Moreover, the focus on publications specifically related to selected key markets leads to a geographical limitation of the study. While this approach allows for a focused analysis of technological drivers in these regions, it limits the generalizability of the findings and may neglect global perspectives.

(d) *Scope of analysis.* The limited number of 11 sources constrains the breadth of the analysis. An expanded database could improve the validity, representativeness, and significance of the findings. In addition, although key technologies were identified in the study, a deeper investigation into their specific roles, functions, and impacts on transformation was not conducted. A more detailed analysis of these aspects could not only enhance the comprehensibility of the results but also their applicability and usefulness for further research as well as for practical applications. Moreover, the study primarily focused on technological factors, while economic, social, or political influences received less attention. An integrative approach that also includes these dimensions could provide a more complete and realistic picture of the transformation.

(e) Practical implications. A stronger emphasis on the practical applications of the research findings could provide companies with concrete recommendations for action. The development of recommendations for action based on detailed analysis could help companies make strategic decisions and prepare effectively for upcoming changes.

5.3. Outlook

Based on the identified technological key drivers and their role in the transformation of the automotive industry, various perspectives for future research are emerging. One potential research direction could involve a detailed analysis of the specific impacts of these key factors on the various stakeholders within the industry. In this context, it would be of interest to evaluate the intensity and scope of the influence of individual drivers. In addition, an in-depth analysis of the interactions between technological drivers and other influencing factors – such as economic, social, and political – could provide further insights into the complexity and dynamics of industrial transformation.

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Conflict of interest

The authors declare they have no competing interests.

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Appendix

Table A1. Literature analysis and synthesis using the concept matrix

Author	Title	Year of publication	Type of media	Journal/ Publisher	Database	Technological drivers				Supporting technologies	
						Connectivity	Autonomous driving	Electrification	Digitalization	Alternative drive technologies	Artificial intelligence
Hoeft[37]	Assessing dynamic capabilities of incumbents in the face of unprecedented industry transformation: the case of the automotive industry	2021	Article	Journal of Strategy and Management	Emerald Insight	X	X	X			X
Turienzo *et al.*[38]	Business models in times of disruption: The connected and autonomous vehicles (uncertain) domino effect	2022	Article	Journal of Business Research	ScienceDirect	X	X		X		X
Yeung[39]	Competitive dynamics of lead firms and their systems suppliers in the automotive industry	2023	Article	Environment and Planning A: Economy and Space	Sage Journals		X	X	X		
Grimm & Walz[40]	Present and future roles of the automotive and ICT sectoral systems in autonomous driving - Using the innovation system approach to assess value chain transformation	2023	Article	Technological Forecasting and Social Change	ScienceDirect		X				
Lopez-Vega & Moodysson[41]	Digital Transformation of the Automotive Industry: An Integrating Framework to Analyze Technological Novelty and Breadth	2023	Article	Industry & Innovation	Taylor & Francis Online	X	X	X	X		X

(Cont'd...)

Table A1. ***(Continued)***

Author	Title	Year of publication	Type of media	Journal/ Publisher	Database	Technological drivers				Supporting technologies	
						Connectivity	Autonomous driving	Electrification	Digitalization	Alternative drive technologies	Artificial intelligence
Ferràs-Hernández *et al.*[42]	Disruption in the automotive industry: A Cambrian moment	2017	Article	Business Horizons	ScienceDirect	X	X	X			
Wittmann[43]	Electrification and Digitalization as Disruptive Trends: New Perspectives for the Automotive Industry?	2016	Book chapter	Springer	Springer	X	X	X	X		
Ziegler & Abdelkafi[4]	Exploring the automotive transition: A technological and business model perspective	2023	Article	Journal of Cleaner Production	ScienceDirect	X	X	X		X	
Kuang *et al.*[44]	Intelligent connected vehicles: the industrial practices and impacts on automotive value-chains in China	2017	Article	Asia Pacific Business Review	Taylor & Francis Online	X	X				X
Frieske & Stieler[45]	Resilient Supply Chains and Robust Strategies for the Transformation of the Automotive Industry	2023	Conference paper	Springer Vieweg	SpringerLink		X	X	X		
Llopis-Albert *et al.*[46]	Impact of digital transformation on the automotive industry	2020	Article	Technological Forecasting and Social Change	ScienceDirect				X		

Author	Title	Year of publication	Type of media	Journal/ Publisher	Database	Supporting technologies				
						(Digital) platforms	Big Data	Robotics	3D printing	Cloud Computing
Hoeft[37]	Assessing dynamic capabilities of incumbents in the face of unprecedented industry transformation: the case of the automotive industry	2021	Article	Journal of Strategy and Management	Emerald Insight					

(Cont'd...)

Table A1. *(Continued)*

Author	Title	Year of publication	Type of media	Journal/ Publisher	Database	Supporting technologies				
						(Digital) platforms	Big Data	Robotics	3D printing	Cloud Computing
Turienzo *et al.*[38]	Business models in times of disruption: The connected and autonomous vehicles (uncertain) domino effect	2022	Article	Journal of Business Research	ScienceDirect	X	X			
Yeung[39]	Competitive dynamics of lead firms and their systems suppliers in the automotive industry	2023	Article	Environment and Planning A: Economy and Space	Sage Journals					
Grimm & Walz[40]	Present and future roles of the automotive and ICT sectoral systems in autonomous driving - Using the innovation system approach to assess value chain transformation	2023	Article	Technological Forecasting and Social Change	ScienceDirect					
Lopez-Vega & Moodysson[41]	Digital Transformation of the Automotive Industry: An Integrating Framework to Analyze Technological Novelty and Breadth	2023	Article	Industry & Innovation	Taylor & Francis Online			X		X
Ferràs-Hernández *et al.*[42]	Disruption in the automotive industry: A Cambrian moment	2017	Article	Business Horizons	ScienceDirect	X	X		X	
Wittmann[43]	Electrification and Digitalization as Disruptive Trends: New Perspectives for the Automotive Industry?	2016	Book chapter	Springer	Springer		X			X

(Cont'd...)

Table A1. ***(Continued)***

Author	Title	Year of publication	Type of media	Journal/ Publisher	Database	Supporting technologies				
						(Digital) platforms	Big Data	Robotics	3D printing	Cloud Computing
Ziegler & Abdelkafi[4]	Exploring the automotive transition: A technological and business model perspective	2023	Article	Journal of Cleaner Production	ScienceDirect					
Kuang *et al.*[44]	Intelligent connected vehicles: the industrial practices and impacts on automotive value-chains in China	2017	Article	Asia Pacific Business Review	Taylor & Francis Online	X				
Frieske & Stieler[45]	Resilient Supply Chains and Robust Strategies for the Transformation of the Automotive Industry	2023	Conference paper	Springer Vieweg	SpringerLink	X				
Llopis-Albert *et al.*[46]	Impact of digital transformation on the automotive industry	2020	Article	Technological Forecasting and Social Change	ScienceDirect					

ARTICLE

Trajectories in digital art illustration and design: A Zimbabwean perspective

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Abstract

Technology has impacted various sectors, and the field of art and design has witnessed notable changes due to these developments. In today's world, digital art illustration has emerged as a prominent and popular form of artistic expression, revolutionizing graphic design, and visual communication, particularly with the rise of technological advancements such as artificial intelligence (AI). This study seeks to explore the development of digital art illustration in Zimbabwe through the lens of the technology acceptance framework. The study focused on artists, lecturers, and students familiar with both traditional art and new technologies. Data were collected through two focus group discussions with students from two higher education institutions. In addition, five lecturers and five practicing artists were purposively selected for in-depth interviews, based on their experience in digital art and their background in traditional art. The data were analyzed using thematic analysis. The findings revealed that digital art has not yet been fully integrated into the art and design curriculum. The study also highlights the critical role of early art and design education in fostering student interest in digital art illustration. Furthermore, digital art illustration can be viewed as an extension of traditional art; therefore, artists should find ways to embrace both forms to their advantage. This integration can be promoted through blended exhibitions, with support from established galleries. For the design field, the study emphasizes the impact of AI and suggests how various stakeholders can incorporate it into their practices to enhance success. The study concludes that investment in technological infrastructure by the government can help promote digital art illustration as a burgeoning sector, creating new job opportunities for the younger, technology-savvy generation.

Keywords: Zimbabwean digital art; Art education challenges; Digital illustration; Technology acceptance model; Art exhibitions; Digital design; Artificial intelligence

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1. Introduction

The process of transforming design concepts into visualizations, and then converting those visualizations into forms that can be evaluated and assessed, is becoming increasingly diverse as digital technologies evolve. The cultural and creative industries are rapidly expanding in the digital era, creating a growing demand for highly skilled individuals proficient in digital art illustration. Digital illustration is a type of art that blends artistic inspiration with human reasoning using computer tools, with new media and digital technologies forming its foundation.[1] As information technology advances, digital illustration has become ubiquitous in various aspects of life, facilitated by the widespread use of computers.

Historically, the development of art illustration can be traced back to the Renaissance period, during which it flourished and spread worldwide as a key component of visual culture.[2] In the 1960s, computer-aided design (CAD) programs such as Sketchpad and PRONTO were introduced to architecture, with the aim of improving the accuracy of geometric drawings and enabling quicker design iterations. Sketchpad, in particular, laid the groundwork for modern CAD systems and the interactive graphical interfaces that are prevalent in today's digital design world.[3] In contrast to traditional art illustration, which requires numerous materials, digital illustration offers a more convenient platform for creative designers to produce and store their work. The rise of digital environments and tools in design has highlighted their potential to transform conventional methods of design representation. However, despite the advantages of digital tools, manual sketching continues to play an essential role in design today.[4,5]

Digital art and illustrations have gained prominence in the online space, offering artists limitless opportunities for self-expression and the exploration of new visual territories through technologies such as graphics pads, universal pens, and graphics tablets. Ping[6] reported that digital art combines traditional illustration techniques with advanced computer technology, providing artists with unprecedented creative possibilities and technical support. According to Chandrakar and Nayal,[7] as well as Hashimi,[8] digital art illustrations have become an effective medium for social awareness campaigns, particularly on issues such as women's rights, leveraging social media platforms to reach broader audiences.

The demand for digital artists has surged globally, driven by the growing popularity of digital art.[9] This trend is also evident in the fashion industry, where the demand for digital fashion illustrators has increased as businesses strive to remain competitive in the fast-paced global fashion market.[10,11] In the fashion sector, designers are expected to generate designs quickly using digital platforms, providing distinctive clothing lines that can serve as key differentiators in a competitive market. In today's world, there are more career opportunities for digital artists as the design sector continues to expand.[12,13] The design industry, which includes fields such as gaming, product design, web development, and others, increasingly requires conceptual technical art, a realm where digital art excels. The growth and accessibility of the internet have acted as a catalyst for the rapid evolution of the digital art illustration world.

Despite the global rise in digital art illustration, this trend has not been as pronounced in some countries. According to Kariati,[14] visual artists such as Masunda lament the shortage of digital illustrators and artists in Zimbabwe, a point previously highlighted by Moyo.[15] In their study on computer graphics in the Zimbabwean film industry, Mauyakufa and Pradhan[16] concluded that filmmakers in Zimbabwe cannot afford the software necessary to modernize their productions. As a developing nation, Zimbabwe faces numerous challenges in accessing software that is crucial to the work of designers. Chipambwa and Chimanga[17] reported that most graphic designers in Zimbabwe rely on pirated copies of the design software, which hinders their ability to fully explore and utilize these tools. In an interview with an emerging artist from Kadelwa Arts in Zimbabwe, Tshuma[18] mentioned that limited access to formal education and training in digital art was a major obstacle to the development of digital art in the country. Tshuma[18] further highlighted that local artists struggle to find specialized courses or institutions that can provide training in digital art and related technologies. Despite the global rise of digital art, Tshuma[18] also stated that cultural differences hinder its adoption within Zimbabwe, as it is often viewed by local artists as less authentic and too foreign. As a developing economy, Zimbabwe has not yet established comprehensive digital art protection laws, which raises significant challenges regarding intellectual property rights. Artists face challenges in preventing unauthorized use of their digital artwork. A study conducted in Uganda, another developing economy,[19] found that inadequate digital skills and the fear of losing creativity were among the challenges faced by art and design teachers when adopting digital technologies in their work. Adeyemi[20] also noted that limited access to technology restricts the ability of African digital artists to create, communicate, and sell their work, further exacerbating existing disparities in the art industry. These issues highlight critical barriers to the growth of the digital arts sector in developing economies, which need to be addressed to foster progress.

The development of the digital art illustration sector depends on adequate investment in software, hardware, and skill development. It is also crucial for educational institutions to develop curricula that respond to technological developments. This study aims to explore the development of digital art illustration in Zimbabwe through an in-depth investigation involving various stakeholders in the creative design sector. The study seeks to answer the following question: How has the availability of digital tools and software impacted the growth of digital art illustration in Zimbabwe?

This paper contributes to the field of design in two key ways. First, it provided an overview of the impact of digital art illustration on the design field, offering a theoretical lens through which global developments in digital art can be assessed and contextualized. Second, the study examines the challenges faced by emerging designers in digital art illustration, with the goal of encouraging stakeholders to actively engage in advancing the sector.

1.1. Theoretical framework

The technology acceptance model (TAM), developed by Davis,[21] served as the theoretical basis for this study. TAM has been widely used in research on user adoption of information technology products. The model includes two key variables: perceived utility and perceived ease of use. It holds predictive value as it can quickly assess the effectiveness and accuracy of technological products. Digital art illustration platforms can be viewed as technological products, making the two key principles of TAM relevant for consideration by artists. In theory, TAM can be applied to study these factors, as well as the impact of digital illustration mediums on consumers' acceptance. According to TAM, artists can only adopt digital art illustration if they recognize the benefits it offers and are well-trained in using the digital platforms.

1.2. Literature review

According to Mazzone and Elgammal,[22] as well as Grau,[23] the intersection of traditional artistic principles and cutting-edge technologies have created a realm of expression that is both visually captivating and conceptually profound. The exponential growth of the digital world has provided a fertile ground for the flourishing of digital art illustration. For artists, the shift from traditional brush tools to CAD technology has opened up new possibilities, allowing them to explore innovative frontiers of creativity. Despite the challenges synonymous with developing nations, such as inadequate infrastructure, digital art illustration has become an effective instrument for artists to showcase their talents and connect with a global audience. The intense competition among software and hardware suppliers has also driven the growth of the sector, with more players entering the information technology industry.

Baca *et al.*[24] highlighted how digital art illustration has transformed the design landscape due to technological advancements. These changes began in developed economies many years ago, leaving developing economies behind in terms of digital art development. In a similar study, Manovich[25] traced the evolution of digital media from its roots in computer science and engineering, emphasizing the transformative impact of computational processes and software development on artistic creation and expression. Manovich[25] further examined how digital technologies enable artists to manipulate and transform digital data to create new esthetic forms and experiences. He also explored the concept of cultural interfaces, referring to how digital media interfaces with and reflects broader cultural, social, and ideological contexts in the internet-driven society.

Digital art illustration enables artists to engage with contemporary issues such as globalization, surveillance, and identity politics, reflecting the complexities of modern society. According to Chikarkova,[26] technology, and digital art have disrupted and reshaped the art landscape in developed countries. Digital technologies have democratized creativity by providing artists with accessible and affordable tools for artistic expression. This democratization has led to a proliferation of diverse artistic practices and voices within the digital art community. However, Chikarkova's[26] observations primarily pertain to individual artists. In the Zimbabwean context, digital art tools are affordable only to a few, offering only a glimpse into how digital art has shaped developed economies. While digital art has the potential to shape developing economies, its impact is currently limited.

Digital technologies have been cited in various contexts as critical for fostering a networked collaboration among artists, scholars, and audiences.[1,2,23,24] Digital platforms and online communities enable artists to connect, share resources, and collaborate on projects in real time, transcending geographical boundaries and disciplinary constraints.[1] These collaborative efforts promote knowledge exchange, skill-sharing, and collective creativity within the digital art community. Digital artists often work with dynamic media, such as code, algorithms, and generative systems, to create artworks that evolve or respond to external stimuli. This emphasis on process-based art challenges traditional notions of artistic authorship and the art object as a fixed entity. In the field of medicine, illustrations are frequently used for teaching, communication, documentation, evaluation, and distribution. According to Heng and Daud,[27] digital illustrations allow for the creation of high-quality images in medical illustrations, even by individuals with little artistic abilities.

While digital technologies offer unprecedented opportunities for artistic experimentation and expression, they also raise ethical, social, and political questions that artists must confront. Grau[23] advocated for a critical approach to technology, urging artists to interrogate its implications for society, culture, and the environment, and to reflect on the ethical dimensions of their practice. Purnell[28] reported that digital art's impact extends well beyond the art world. As digital technologies become increasingly integral to modern life, digital artists play a key role in shaping our perceptions of the world. From movie special effects to mobile application design, digital art is ubiquitous, and its influence is only set to grow. The ability to create and communicate visually in the digital realm is now vital for human expression and communication in the 21st century, a reality further underscored by the introduction of artificial intelligence (AI) into the art production process.

According to Fang and Jiang,[29] AI has revolutionized the digital art field in recent years, offering artists new opportunities to explore and produce novel pieces. By inputting a dataset or prompt into an AI platform, artists can generate new, original images based on those inputs. This process has allowed artists to experiment with new visual styles and create artworks that push the boundaries of traditional art forms.[30] However, the use of generative AI in art and design raises questions regarding authenticity and intellectual property.[31] On the other hand, AI technology enriches art education by providing access to digital collections and personalized guidance, enabling students to explore diverse artworks and cultures.[32-34] Like generative algorithms, AI is transforming digital art by enhancing teaching methods, esthetic understanding, and student engagement through tools such as simulated annealing, CAD, and computer vision for artwork analysis and production.[35] The evolution of digital art is increasingly intertwined with AI, and its continued integration demonstrates how AI interacts with all forms of art.[26] Sophisticated generative models and Internet of Things technologies are expanding the tools and resources available to the digital arts sector. These advancements have accelerated innovation in art education while providing students with broader platforms for artistic expression.[29] However, other scholars[2,26,36,37] have raised concerns about the use of AI in digital art. Some argue that AI diminishes the artist's role in the creative process, as algorithms are responsible for generating the artwork rather than individual human artists. Despite these concerns, the incorporation of AI into digital art has opened up new avenues for experimentation and innovation. Artists now collaborate with AI as a tool and explore new forms of expression that were previously unimaginable. As AI continues to evolve and advance, the possibilities for digital art illustration are limitless.[38] Artists are just beginning to scratch the surface of what AI can offer to the world of art and innovation.

Emerging technologies are significantly transforming the landscape of digital art, introducing innovative methods for creation, interaction, and distribution.[39] Key advancements include virtual reality (VR), augmented reality (AR), AI, and blockchain technology, each contributing uniquely to the evolution of digital art.[39,40] According to Nocheseda *et al.*,[41] the integration of 3D printing and AI is becoming increasingly important as more contemporary art pieces are being produced using these techniques. Ozdemir[39] noted that non-fungible tokens have gained significance in the development of digital art, enabling artists to sell, buy, and distribute their work, thereby adding complexity to the discussion on the commodification of digital art.

The visual and creative arts industry in Zimbabwe has faced several challenges, as evidenced by the closure of prominent and well-established galleries such as Delta Gallery and Chapungu Sculpture Park.[42] These closures and reduced activity in the arts sector have been attributed to the political and socio-economic challenges confronting the nation. While there are still art buyers or collectors, the economic difficulties, along with the digital shift in art and design, have created a gap in the sector. According to Moyo,[15] digital art exhibitions, such as the one curated by Dananayi Muwangiwa, have introduced the concept of digital art to the Zimbabwean scene. Muwangiwa's exhibition, which focused on AR as a digital technology, was recognized as a success in its own right.[15] With the advent of COVID-19, which restricted physical exhibitions to control the spread of the virus, the demand for digital art illustrations grew significantly worldwide. Artists and creatives in all design spheres sought ways to remain active in their industry. Despite the positive developments in digital art, it should be noted that the general consumption of art in developing countries is still in its infancy.

Art and design education plays a pivotal role in shaping digital art illustration as a subsector of this area. Mushohwe[43] advocated for the introduction and full support of art as a formal subject in early childhood education, rather than treating it as a mere hobby. In terms of training artists in digital art illustration, one prominent institution is the Zimbabwe Institute of Vigital Arts (ZIVA), which focuses on developing the visual and digital arts. According to Makoni,[44] ZIVA has been instrumental in nurturing young talents in animation and digital art illustration. Moyo[15] further emphasized the need for curricula at institutions of higher learning to fully support the teaching and learning of digital art, arguing that this approach helps to foster early interest among students.

2. Materials and methods

This study adopted a qualitative research approach to gain insights into digital art illustration from the Zimbabwean perspective. Denzin and Lincoln[45] defined qualitative research as a study in which data and findings are not purely statistical but are instead naturalistic in nature. According to Maxwell,[46] qualitative research methodology comprises four key aspects: Building connections with the subjects, sampling the subjects, data collection, and data analysis. Each of these aspects significantly impacts the value and validity of the study's findings.

Decision-making regarding digital art illustration from the artist's perspective can be understood through TAM. TAM proposes that perceived utility and perceived ease of use are the two main criteria influencing technology adoption and use. Perceived usefulness refers to the artist's belief that using a digital platform will improve their artwork, while perceived ease of use relates to the amount of effort the artist is willing to invest in using the platform. A positive relationship between these two principles of TAM is expected to lead to greater adoption of digital art platforms by artists. Scholars[47-49] argued that TAM's static nature and individual-centric focus do not adequately account for the complexities of modern technological environments, such as those found in the metaverse and VR, which demand a more dynamic approach.[50] Despite Ajibade's[49] criticism that TAM primarily focuses on personal perceptions and overlooks broader social and cultural influences on technology adoption, this study found the TAM model to be applicable, as digital art serves as a form of self-expression.

2.1. Participant selection

A total of 10 in-depth interviews were conducted, involving five lecturers and five practicing artists. Two focus group discussions were also held, each with a group of 10 students enrolled in a graphics module at a local university. The artists were selected based on the information gathered at an art exhibition event held at the National Art Gallery of Zimbabwe. The criteria for selecting the artist participants were as follows: (i) the participant should have curated an art exhibition showcasing their works at an established gallery, either locally or regionally; (ii) the participant should have been a practicing artist for at least 5 years; and (iii) the participant should have some level of appreciation for digital art. The study also sought to sample lecturers or instructors from institutions of higher learning, based on the following criteria: (i) the participant should be a teacher at a university, polytechnic, or college associated with higher education; (ii) the participant should have taught or currently teach courses or modules such as illustration, drawing, graphic design, or related fields; (iii) the participant should have at least 5 years of experience as an instructor. The focus group discussions included students from one university's Faculty of Art and Design and one polytechnic college at a local university. The decision to focus on final-year students at the university was motivated by the fact that these students had completed an internship period of at least 8 months, gaining practical experience in various areas of specialties such as fashion design, graphic design, product design, and fine art. At this institution, all students in the faculty take the same modules in drawing and graphic design, thus ensuring a shared appreciation for both traditional and digital illustration. For the polytechnic focus group students, students in their 2nd year of the Higher National Diploma in Creative Arts program were selected.

2.2. Research data collection

All interviews and focus group discussions were conducted between November and December 2023. Invitations to the artists were extended only after initial engagements at art exhibitions, where informal discussions on global general art movements were held. These interactions allowed the researchers to build trust and establish relationships with the artists, ultimately leading to the creation of a social media group for ongoing discussions related to art and design in Zimbabwe. Interviews were scheduled at times convenient for all participants and lasted up to 1 h. Field notes were taken during the interviews and were subsequently used in the data analysis process. The interviews focused on various topics, including digital art, technological advancements, user experience, digital art consumption, as well as the challenges and opportunities faced by digital artists. The interview questions were open-ended and semi-structured, enabling participants to provide detailed feedback, thus resulting in rich information. A summary of the participants is provided in Table 1, where each participant is assigned a code, along with a brief overview of their experience. To ensure data saturation, the selection criteria for participants were strictly enforced, ensuring that all interviewees were knowledgeable about digital art illustration.

2.3. Analysis and results

The study employed the grounded theory to code, analyze, and organize the data, leading to new insights into digital art illustration.[51] As digital art illustration is a new and emerging field with the potential to transform the art and design landscape, grounded theory was chosen to identify the underlying patterns and structures contributing to its emergence and growth. The data analysis process began with data collection, followed by open coding, axial

Table 1. Summary of profiles of interviewed participants

Participant	Identity	Gender	Age (yrs)	Experience (yrs)	Background
Lecturer (University)	LU1	M	41	11	Fashion design; graphic design
Lecturer (University)	LU2	M	45	8	Drawing; illustration; graphic design; animation
Lecturer (University)	LU3	F	52	24	Drawing; illustration; graphic design; product design
Lecturer (College)	LC1	M	34	7	Animation; graphic design
Lecturer (Polytechnic)	LP1	M	32	6	Drawing; illustration; sculpture
Artist	A1	M	30	12	Animation; graphics
Artist	A2	M	34	10	Fine art
Artist	A3	M	45	25	Sculptor; ceramics
Artist	A4	F	28	5	Graphics
Artist	A5	F	24	6	Art illustration

Abbreviations: A: Artist; F: Female; LC: College lecturer; LP: Polytechnic lecturer; LU: University lecturer; M: Male; yrs: Years.

coding, and finally, selective coding. This iterative process continued until the researchers determined that theoretical saturation had been reached.

Core categories were then synthesized and integrated into one main theme or sub-theme to form a coherent standpoint. The focus group discussions also generated key ideas, and some general quotes about digital art illustration were captured. The obtained data were compared with the interview data to identify similarities or nuances that aligned under the same theme or sub-theme. The unit of analysis for the focus group discussions was the group as a whole. The study utilized a constant comparison analysis method for the focus group discussion data, as recommended by Leech and Onwuegbuzie.[52]

3. Results

All the interviewed participants met the criteria set for validating the data, as shown in Table 1. The codes assigned to the participants ensured anonymity. Male participants constituted 70% of the sample, compared to 30% of female participants, although the selection was not gender-based. Regarding knowledge, all participants provided insightful perspectives on digital art illustration in Zimbabwe. Major themes were extracted from both the interview data and the focus group discussions, as presented below.

3.1. Benefits of digital art illustration

It was highlighted that digital art illustration is a growing sector, offering a wide range of job opportunities within the art and design field. This expansion creates a lucrative area for younger students to enter the art sector, as noted by one lecturer:

> *The growth of digital art means more opportunities for tech-savvy youths, who are increasingly exposed to technology as digital technologies advance. We expect more students to start enrolling in our program as we have introduced more digital components compared to traditional art, such as life drawing (LU3).*

The decision to introduce more digital learning courses or modules was also supported by another lecturer, who stated that career opportunities for students have expanded, as the demand for these new digital skills grows. One artist mentioned that digital art illustration has also benefited the local film industry, with more production houses investing in new equipment and technologies, thus opening up more roles for digital creative. Furthermore, the art and design sector has the potential to contribute significantly to the country's gross domestic product through revenue generated from digital exhibitions. Increased competition among digital artists was also noted as a positive factor, as it drives the quality of their work. As one participant in the focus group discussion pointed out, digital art serves as a powerful marketing tool, helping to sell the country as a brand by enabling artists to creatively share Zimbabwe's story. This was further supported by another artist, who mentioned that nowadays, it is easier to share folktales through digital art, thus preserving their culture and heritage. Digital art illustration also plays a critical role in education and communication. The participants noted that educational materials, such as textbooks and online resources, increasingly use illustrations to aid in understanding complex concepts. One artist emphasized:

> *Digital art can result in better data visualization using artistic elements, making complex models easier to understand and share (A3).*

This sentiment was echoed by the students, who noted that digital illustrations can bridge language barriers, making information more universally accessible.

3.2. Digital art education

Despite being taught in their respective two institutions, students reported that the skills they acquire do not adequately prepare them for real-world application. One student shared:

> *The time allocated for the course on digital illustration is very limited, and as students, we end up aiming only to pass the exam Focus Group Discussion One (FGD1).*

This case reflects the need for a curriculum review to ensure that the content delivered is more beneficial to students. It was also highlighted that students face challenges such as a shortage of support resources in their studios, particularly a lack of high-performance computers needed for digital art. The study further revealed that some students entering a new degree lack a strong background in art education, making it difficult for them to grasp some of the basic concepts essential to digital art. One interviewee also commented on the influence of AI on digital art development:

> *Students now prefer to use AI for digital illustration on various platforms, which undermines the individual creativity that is traditionally associated with art, making assessment difficult (LC1).*

This comment suggests a need for curriculum revision to incorporate new technologies such as AI, VR, and AR in art and design education at the higher education level. Another lecturer noted that digital art promotes problem-based learning among students, encouraging personal development, though some students may not recognize its benefits. For digital art to flourish, one participant stressed the importance of supporting art and design education from the grassroots level. This approach would allow students to develop and nurture their skills early, facilitating well-informed career choices. The study also found that while Zimbabwe's high school curriculum includes CAD-related requirements in subjects such as Art and Design, Textile Design, and Design and Technology, there is a lack of foundational knowledge in CAD among students when they enter higher education institutions. This gap makes it challenging for them to grasp CAD concepts effectively.

3.3. Digital art development

The results from the study indicated that, to the best of the participants' knowledge, only three digital art exhibitions have been held in the past 5 years. One interview participant stated:

> *The growth of the digital art industry can only succeed if there is a corresponding demand for such art. Therefore, digital art exhibitions are not very popular, as traditional art itself is not widely appreciated among the local population (LU1).*

The above sentiments suggest the lack of enthusiasm for traditional art has directly impacted the growth of the digital art sector. Another critical issue raised by the students was the financial capacity to purchase graphic software that could significantly improve their creative output. Although some software, such as CorelDraw, offers monthly subscriptions, it was noted that financial constraints prevent some students from renewing their subscriptions. In addition, the cost of the hardware required for digital art illustration was considered prohibitively high by the majority of the respondents. Digital illustration requires powerful computers or tablets with high-resolution graphics, which are often expensive. The participants also discussed developments in AI, where users can generate images from text prompts. This technology has led to concerns that anyone who can write a good prompt, regardless of their art background, can now claim to be a digital artist.

3.4. Collaboration in digital art

The interviews highlighted the need for knowledge-sharing among artists, which could significantly contribute to the development of the digital arts sector. One artist emphasized the importance of encouraging students to engage in more projects through assignments, as this effort would help them discover hidden talents. Fostering partnerships between local and international institutions of higher learning was also suggested as a strategy to enhance students' digital art illustration skills. Another interviewee proposed that:

> *Colleges can partner with generative AI developers to organize online sessions that can help local digital artists understand and appreciate AI better (A5).*

She further suggested that such collaborative efforts could directly benefit students, potentially providing access to cheaper payment plans or job opportunities on AI platforms. In today's technological world, no one can be an expert in all emerging technologies. Thus, as suggested by another participant, there is a need for cross-pollination between high school teachers and university lecturers. This action would ensure that educators are equipped with the latest knowledge, enabling them to teach digital art more effectively in schools. The students also mentioned that participating in online design contests that require illustrations could open up more opportunities. Such contests offer the potential for students to earn money while continuing to learn and develop their skills.

3.5. Government support

The government was identified as a key player in the development of digital art in Zimbabwe. Art galleries that faced viability issues could be supported by government funding to reopen and serve as hubs for promoting digital art. The participants also highlighted the need for the National Gallery of Zimbabwe to promote digital exhibitions, as they could encourage young artists to explore digital art. As a developing nation, Zimbabwe has cultural exchange programs with several developed countries where digital art has flourished. Promoting digital art through these programs and offering scholarships could yield significant rewards for local artists. The participants also emphasized the importance of the government actively promoting art as a core subject from the primary education level. Early exposure to art education helps students develop their skills at a young age. In the corporate sector, companies can play a significant role in promoting digital art development. Some participants argued that such companies could be incentivized with tax rebates by the government in recognition of their contributions to an important sector of the economy. The study also revealed that the government owns all the higher education institutions involved in this research. Therefore, investing in the necessary infrastructure and resources should be prioritized if these institutions are to produce competent digital illustrators.

4. Discussion

The technological accessibility available to Zimbabwean designers plays a crucial role in shaping the development of digital art illustration. With the proliferation of smartphones and affordable software options, many emerging artists are now able to explore digital mediums without substantial financial investment. This democratization of technology in art and design has created a fertile ground for the growth of digital art illustration, where tech-savvy young designers are eager to explore the possibilities that technology offers. However, the study also revealed that established artists, who often have access to more advanced tools and resources, are able to produce intricate designs and high-quality outputs. This disparity can result in unequal visibility among creators at different stages of their careers. Consequently, this cascade of events creates an uneven playing field, affecting how designers navigate their careers in digital art illustration. Culturally, Zimbabwean art is rich with ideas that could be effectively promoted through digital platforms. The integration of culture and technology holds significant potential for economic growth, as it enables Zimbabwean artists to reach wider audiences. The contrast between those who embrace traditional elements of art and those who favor modern minimalism underscores the diversity within this artistic domain.

The study also revealed that the rise of digital art illustration has sparked debates about its impact on traditional art forms. Some purists argue that digital art lacks the authenticity and tactile quality of traditional mediums such as painting and sculpture. However, many contemporary artists view digital illustration as an extension of traditional practices rather than a replacement. This view aligns with Moyo's[15] assertion that traditional art will not be substituted by digital art; rather, the two can coexist and complement each other. The blending of digital art illustration with traditional art could give rise to hybrid art exhibitions, offering a new dimension to the field. Education plays an important role in human capital development, and as Mushohwe[43] suggests, the teaching of art and design should be promoted from the early levels of education. Digital art education fosters new practices among artists, aligning with the needs of the Fourth Industrial Revolution, which demands creative talents in a complex and evolving market. The intense competition among software companies has benefited users, as more flexible and affordable packages — often with educational discounts for students — are now available. Institutions of higher learning should explore ways to negotiate subscription packages for their enrolled students, ensuring they can take full advantage of the various strengths offered by different platforms. While artists increasingly utilize digital platforms to reach broader audiences and showcase Zimbabwean culture on the global stage, challenges persist, including limited access to technology and the need for greater institutional support for artists. This duality reflects the ongoing tension between tradition and modernity in Zimbabwe's artistic expression.

Another key issue that could hinder the success and growth of digital illustration is the ethical concerns surrounding authorship, copyright, and the use of AI-generated content. The ease with which digital images can be replicated and modified raises serious questions about ownership and originality.[2] Digital artists, therefore, must navigate the complexities of copyright law, particularly when drawing inspiration from or referencing existing works. Furthermore, the rise of AI-generated art prompts debates about the role of the artist in the creative process and its implications for artistic integrity. Finally, the increase in job opportunities resulting from digital art, as mentioned in the results, is also supported by a previous study.[13] If digital art illustration is embraced by all stakeholders, it could significantly contribute to the economic growth of the nation.

5. Conclusion

The study concludes that digital art illustration has become an integral part of contemporary art and design, significantly influencing various industries and transforming how artists create visual content.

Its historical evolution, technological advancements, diverse applications, and impact on traditional art forms highlight the dynamic nature of this medium. Ethical issues surrounding the use and adoption of AI in digital art illustration will continue to shape its trajectory worldwide, necessitating the development of AI policies at institutional, corporate, and government levels. Digital art illustration stands as a testament to the power of creativity and innovation in an increasingly digital world, offering exciting possibilities for both artists and designers. Digital artists should take advantage of online courses to enhance their proficiency with chosen software, while also creating digital portfolios to showcase their work in various online communities. Engaging in online workshops, seminars, and communities can help build networks and foster collaborations on joint projects. For local Zimbabwean artists, digital art offers numerous benefits, such as efficiency, shareability, versatility, and cost-effectiveness, despite the higher initial investment in equipment. To fully realize these benefits, digital artists must utilize advanced software and hardware tailored for digital illustration, explore AI-driven techniques, and leverage social media platforms to monetize their artwork. The role of education in the development of digital art illustration cannot be overstated. Digital art has already made a significant positive impact in fields such as education, product design, fashion design, marketing, animation, advertising, and the gaming industry. Its ability to quickly produce solutions that can be shared with multiple iterations is reshaping the art and design world. Governments should develop flexible cultural policies that can adapt to rapid changes in digital technologies and consumption patterns. This effort includes recognizing the unique needs of digital artists and their audiences, which is crucial for the growth of the digital art industry. A review of the Zimbabwean art education curriculum is critical to incorporate emerging technologies in the development of digital art, ensuring it is inclusive and accessible to all students. Developing a policy for digital art and the creative sector requires the involvement of key stakeholders, including art educators, designers, artists, businesses, and community members. Their engagement in policy-making ensures a more comprehensive and widely accepted solution for the digital arts sector. Finally, the study concludes that art galleries and other key stakeholders have an important role to play in promoting digital art illustration as an extension of traditional art. Hybrid exhibitions could be a viable option to expand the reach of digital art illustration. By strengthening digital art education, the Zimbabwean government could enhance the skills of the creative sectors, potentially leading to higher employment and greater economic resilience.

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Legitimizing design thinking: Addressing barriers to corporate adoption

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Abstract

The design domain has long been recognized as a source of value creation, with a recent paradigm shift in both academic and practitioner circles conceptualizing design as a comprehensive innovation management practice. Design thinking (DT) has gained prominence for fostering engagement and confidence in creative processes. However, outcomes can be influenced by various factors and conditions, making direct attribution to DT challenging. While organizational maturity can impact DT implementation, this relationship is complex and warrants further investigation. More in-depth research and appropriate methodologies are needed to assist organizations in establishing the legitimacy of DT, acknowledging that legitimacy often derives from the perceived quality of work outcomes, which is inherently subjective. Therefore, it is essential to develop more objective criteria and evaluation methods to provide a clearer and more reliable basis for assessing the success and impact of DT initiatives. This paper addresses the need for legitimacy in adopting DT as an innovation strategy, with a focus on both individual and social structural perspectives. Drawing on organizational workplace theories and employee perceptions, we developed and tested hypotheses to overcome barriers to the adoption of DT. Although based on a small sample size, our study offers valuable insights into the factors influencing DT adoption within organizations. Using a quasi-experimental approach, we examined how organizational practices, leadership, and physical spaces affect the legitimacy and widespread adoption of DT. By assessing both qualitative and quantitative indicators, we combined participant feedback with observable behaviors for a more comprehensive evaluation. Recognizing the subjectivity of legitimacy measurement, we enhanced our approach by integrating multiple data sources. This study lays the groundwork for future research, refining legitimacy assessments and investigating the long-term impact of DT adoption. We hope our findings inspire further exploration of additional variables that influence the success of DT across diverse organizational contexts.

Keywords: Design thinking; Legitimacy; Innovation management

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1. Introduction

The significance of design as a source of value creation has been explored for decades. Design thinking (DT) has emerged as a key driver of innovation, sparking growing discussions about its role in both design and management.[1,2] The need for innovation to succeed in saturated markets served as the starting point for these discussions. Over time, DT has evolved into a strategic tool. The main factors driving the rise of DT in management are the increasing demand for innovation, creativity, and new approaches to solving complex business challenges.[3,4]

A new interpretation is emerging in both academic and practitioner communities: design as a comprehensive innovation management practice, encompassing a new set of processes, attitudes, and capacities. DT is gaining traction in the corporate sector as a catalyst for developing unique user experiences, new companies, strategic transformation, and organizational and cultural changes.[5] Some companies have used DT to reshape their cultures, making them more adaptive and customer-focused. This process includes active thought, where the nature of an issue is questioned, driving learning and changing attitudes and behaviors.[6] DT has transformed businesses across industries, with companies like Apple Inc. and IDEO leading the way by embedding it into their cultures. At Apple, Steve Jobs fostered a design-driven culture that inspired others, such as Airbnb. In 2009, Airbnb's leadership identified, through DT, that low-quality photographs on their website were hindering bookings. By replacing them with professional images, revenues doubled within a week, demonstrating how DT can address business challenges. Airbnb's leadership successfully balanced an analytical, data-driven approach with intuitive and creative thinking, combining a deep passion for the company's product with genuine customer empathy and integrating linear planning with a willingness to experiment. Airbnb's ability to apply DT strategically was largely due to the mindset of its leaders and the dynamic, adaptive startup culture they cultivated. Both co-founders, Chief Executive Officers Brian Chesky and Joe Gebbia, have backgrounds in design, which played a crucial role in this approach.[7]

DT has emerged as a human-centered yet goal-oriented approach to innovation, prompting enterprises to transform how they think and operate.[8] A substantial body of research has validated DT; however, gaps remain, particularly regarding the adoption barriers that become more critical as organizational maturity increases. Much research has confirmed that obstacles to DT adoption exist in businesses,[9-14] recognizing that these barriers become more significant as a company matures. Given the lack of extensive research and suitable techniques to help businesses navigate these obstacles from both individual and organizational perspectives, this study focuses on the legitimacy of adopting DT as an innovation strategy, exploring these barriers in depth. To our knowledge, previous research has not thoroughly investigated the legitimacy implications for both the individual and the social structure, an important consideration for engaging an organization with DT in the long term.

Adopting DT in companies can be difficult due to a lack of understanding of the approach. Employees may be unaware of what DT entails or may misinterpret it due to ambiguous information.[13] Furthermore, the internal integration of DT is often limited by uncertainty about its outcomes and the success of its application.[3] Despite these challenges, DT remains crucial for establishing and expanding companies seeking to differentiate themselves in the market.[2,4]

Kwon *et al.*[15] developed a multilevel conceptual framework to explore the impact of individual employees' perceptions of communication patterns on their job engagement. According to these authors, three levels of factors influence the alignment of voice practices as "best practices," contributing to work engagement: macro-level national culture (specifically, the degree of power distance), meso-level organizational climate (including empowering leadership and participation levels), and micro-level relationship quality between employees and supervisors (leader-member exchange). This paper aims to explore how organizations can legitimize the adoption of DT at both the individual and social structural levels. The investigation drew on the three levels outlined by Kwon *et al.*[15] and incorporated organizational perspectives on the effects of the physical environment, as discussed by Seifried and Wasserbaech.[3]

This study is based on empirical research in which hypotheses were developed from the topics mentioned above, then tested and validated using a quasi-experimental approach and quantitative analysis of the results. Data collection was conducted immediately after specific work activities, allowing for real-time insights. This quasi-experimental approach provides empirically grounded insights, contributing to a comprehensive understanding of the factors influencing the successful implementation of DT within individual and organizational structures.

By proposing and testing a set of hypotheses to address this challenge, this paper fills a crucial gap in the literature regarding the need for legitimacy in DT adoption. It enhances understanding of why legitimacy is critical and anticipates potential approaches to overcome this limitation, both at the front end of innovation (generating new ideas and developing new products/services) and at the back end of innovation (commercialization of an existing product). The study's findings will be valuable for numerous organizations worldwide that have faced this limitation, thus improving DT implementation, advancing knowledge, and contributing to the theory with a set of testable hypotheses validated through an in-depth, real-life case study on how DT gains legitimacy within organizations.

2. Challenges legitimizing DT

Legitimacy is crucial for gaining acceptance of new concepts within a social system. In the context of DT, ensuring legitimacy involves addressing challenges such as the need for data to persuade decision-makers, the introduction of uncertainty and abstract ideas, and bridging the gap between DT and traditional business processes. Organizations must overcome resistance and build legitimacy to adopt DT successfully.[13,14,16]

After an in-depth investigation, we identified the main challenges legitimizing DT: (i) convincing decision-makers without data or numerical evidence is complex, necessitating improved communication strategies;[10] (ii) DT introduces uncertainty and questions existing practices, requiring a shift in mindset;[12] (iii) proving legitimacy may lead to small, incremental innovation projects;[10] (iv) bridging the gap between DT and traditional processes encounters resistance due to ambiguity and required mindset shifts;[11] (v) mismatches in values and norms between organizations and DT create challenges in demonstrating DT's advantages;[13] and (vi) legitimacy enhances stability and clarity but is not always equally supported by organizational behavior.[14]

The main challenges outlined above can be grouped into four key topics, which are explored in the following subsections.

2.1. Macro-level national culture

National culture significantly shapes organizational norms and influences employee attitudes and behaviors at a macrolevel. Power distance, a critical aspect of national culture, determines decision-making authority within organizations and affects employee voice.[17] Voice practices are crucial for promoting justice and legitimacy within an organization.[18] Individual cultural orientations regarding power distance influence employees' willingness to express their thoughts.[19] Understanding individual-level factors such as attitudes, personality, motivation, and experiences is essential.[20] Adopting DT can be challenging due to organizational culture issues that hinder the full realization of DT's potential.[21] Mismatches with existing procedures, structures, and organizational culture pose significant obstacles to DT adoption.[3,22] Implementing DT often requires substantial organizational changes, including reassessing traditional values and norms. As Seifried and Wasserbaech[3] highlighted, successful DT adoption not only involves creating the appropriate physical spaces but also demands a shift in organizational culture. The conflict between traditional decision-making models, which tend to be hierarchical and linear, and the rapid, iterative thinking central to DT, can create resistance within organizations. Balancing innovation with organizational harmony is essential.

The "creative confidence" approach aims to empower employees by fostering creativity and change, allowing them to propose and implement changes based on their values and attitudes.[23] This approach mitigates the production blockage effect, particularly in environments with lower power distance and a focus on employee voice.[24]

2.2. Mesolevel organizational climate

At the mesolevel, the organizational environment, as defined by Patterson *et al.*,[25] involves the exchange of ideas and impressions among employees within teams and departments. A participatory climate is essential for encouraging employee voice, fostering the sharing of new ideas, proposals, and opinions from various perspectives, and involving employees in decision-making and problem-solving at work. The attitudes and practices of top management are critical in creating a participatory culture.[21,26] Employees continuously observe and assess leaders' behaviors, which shape the meaning of specific workplace climates.[27] Human resource management practices contribute to a positive organizational environment, but leadership support is essential.[28]

Active engagement by top management in DT practices encourages a culture that promotes desirable attitudes and behaviors. Leadership empowerment and the sharing of power with subordinates create a participative DT environment, fostering employee involvement in decision-making and increasing intrinsic motivation.[29,30]

Empowering leaders can encourage autonomous employee behaviors, such as problem-solving and decision-making in DT, reducing the need for direct supervisor involvement.[31] This approach aligns with the goals of voice practices, allowing employees to influence workplace decision-making. Leaders who actively involve employees in DT decision-making intentionally incorporate their input, create outlets for voice, and establish a "strong voice-supportive atmosphere."[32] Employee pulse surveys empower employees, boost confidence and focus, enhance workplace happiness, and improve the overall organizational climate.

2.3. Microlevel relationship quality between employee and supervisor

At the microlevel, the quality of the relationship between employees and their supervisors plays a pivotal role in translating employees' job experiences into attitudes and behaviors. Supervisors are key agents in implementing direct voice practices, and their interactions with employees significantly influence employees' comfort and willingness to express their opinions. Trust in supervisors' ability to take advice seriously and apply it in decision-making is crucial.[17] The effective exchange of viewpoints in diverse teams is encouraged; however, obstacles to sharing and leadership approaches can impact the outcomes.[21,33] A shortage of professionals with experience in DT has been identified as a challenge, requiring further training and development.[34] Corporate-level managers play an essential role in legitimizing and guiding the adoption of new practices within the organization.[21] Leadership legitimacy and the willingness to follow established guidelines influence team commitment.[35,36]

For the successful implementation of DT, a high level of preparation from employees, managers, and executives is necessary. Leaders should assess the organization's understanding and application of DT, identify areas that need improvement, and consider pilot projects to provide hands-on experience. Pereira *et al.*[21] confirmed that DT supports organizational change over time in response to various factors, such as market trends, feedback, resource constraints, and business requirements.

Managerial support and the ability to legitimate new practices are vital for effective implementation.[37] A lack of legitimacy and concerns over output can lead to managerial disinterest and skepticism, potentially hindering the adoption of new practices.[9]

2.4. Organization structures

This study underscores the importance of workplace design in legitimizing the adoption of DT. An organization's physical environment can catalyze change by breaking down hierarchical boundaries, promoting creativity, facilitating prototyping, and enhancing the overall rate of learning and change.[3] Flexible and agile working environments are vital for fostering innovation and reshaping mindsets. DT requires dedicated physical spaces distinct from traditional offices, designed to encourage creative thinking. These DT rooms should support in-depth exploration, with features such as writable walls, movable furniture, and areas for transitions and relaxation to facilitate social interactions.[3] Leifer and Steinert[38] identified five types of creative spaces: personal, collaboration, presentation, experimentation, and transition/relaxation zones.

The workplace's architectural style is crucial for learning and innovation, incorporating open spaces, movable furniture, writable walls, and various prototype materials.[3] Employees should find these spaces inviting and comfortable to encourage active participation and innovation. The use of DT artifacts and innovative workplace designs plays a transformative role in shifting mindsets and impacting underlying norms, values, and assumptions. Creating dedicated physical locations and incorporating training and promotional materials are considered critical to the successful implementation of DT within an organizational context.[13]

3. Empirical study

3.1. Development of research hypotheses

Based on the literature, four hypotheses were developed to be tested and validated in the field. National culture shapes organizational norms and defines appropriate employee attitudes and behaviors.[17] Power distance, a crucial element of national culture, influences the level of decision-making authority within organizations and affects employee voice. A high power distance orientation may hinder communication and decision-making participation by less powerful employees.[15] Individual-level factors such as attitudes, personality, motivation, and expectations also impact employee voice.[20] Organizational culture issues can pose challenges to the adoption of DT, leading to a mismatch with existing procedures and culture, and risking a lack of consideration for stakeholder needs.[21] Reducing power distance in employee–manager relationships can legitimize DT adoption by promoting participation and a more participatory climate. The creative confidence approach[23] aims to engage employees in innovation by empowering them to propose and implement changes based on their values and attitudes. This effort reduces the production blockage effect and enhances innovation. A stronger relationship between employees and management is associated with a lower power distance, meaning less hierarchy and a more equal distribution of power within the organization. Lowering power distance in employee–manager relationships strengthens the legitimacy of DT adoption by fostering a stronger connection between perceptions of voice practices and a participatory climate, thus providing opportunities for employees to participate in decision-making within the team or organization.

3.1.1. Hypothesis 1: Organizations require creative trust

Creative trust refers to the belief that employees' ideas and suggestions are valued and taken seriously by management. This trust creates an environment where employees feel more motivated to contribute their ideas, leading to greater acceptance and legitimization of DT. For innovation to thrive within a company, it is essential that employees feel that they have the freedom and confidence to propose innovative ideas and actively participate in the implementation of changes.[23] As a result, the adoption of DT becomes more legitimate due to a stronger relationship between the perceptions of both employees and management, fostering a participatory climate.

3.1.2. Hypothesis 2: Companies need to create a culture of openness and feedback

The organizational environment must cultivate a participatory culture to promote employee engagement. This can be achieved through leadership attitudes and practices.[15,26] Human resource practices also contribute to creating a favorable atmosphere, but leadership support is crucial.[28] Active participation by top management in DT practices can create a climate that fosters the desired attitudes and behaviors.[39] Empowering leadership, which involves sharing power with subordinates, can encourage employee participation in decision-making and raise their intrinsic motivation.[29,30] Leaders who encourage employee participation in DT decision-making intentionally incorporate employee ideas and feedback, providing avenues for voice. This behavior creates a strong, voice-supportive atmosphere that promotes employee engagement in DT.[32] Companies must create a culture of openness and feedback, with voice practices that allow employees to speak openly. Exhibiting trust makes employees feel valued and connected to leaders and teammates. Empowering leaders in a culture of openness and feedback contribute to legitimizing DT adoption by allowing employees to communicate openly, feel valued, and foster stronger connections with both leaders and colleagues.

3.1.3. Hypothesis 3: Organizations need leaders trained in DT

The success of the implementation of DT in an organization depends on several factors, such as the perception of employees and supervisors toward DT, the quality of the supervisor–subordinate relationship, and the competence of managers in executing DT practices.[40] Managers play a crucial role in legitimizing the new practice and guiding teams effectively.[37] However, challenges related to legitimacy and output may lead to skepticism and decreased management support. Thus, it is essential to train managers in DT and incentivize its use to address real-world challenges. Both employees and executives must understand and feel comfortable with DT. Organizations need leaders who are well-versed in DT, and greater emphasis should be placed on building leadership competence in this area to ensure the effective adoption of digital transformation practices. Well-trained managers contribute to legitimizing DT adoption by enhancing their ability to support the practice and guide teams successfully.

3.1.4. Hypothesis 4: Organizations need a physical space designed specifically for the use of DT

A mismatch between organizational culture and the workspace can hinder DT adoption.[41] The design of the workplace is crucial to facilitating DT, as it can transform the physical environment to foster learning and change. Flexible and agile workspaces are essential for DT, supporting creativity and prototyping. To encourage DT, organizations should incorporate five types of creative spaces: personal, collaboration, presentation, experimentation, and relaxation areas. A flexible work environment with adaptable physical features – such as movable furniture and writable walls – along with infrastructure tailored for project teams is necessary. The architectural design of the workplace should be inviting to encourage active participation and innovation. Creating physical spaces and artifacts specifically for DT use can legitimize its adoption by shifting mindsets, norms, and assumptions, thereby promoting innovation. DT artifacts and dedicated spaces have been shown to influence these mindset changes. Establishing these physical locations and artifacts, such as training materials and promotional content, is crucial for making DT work in an organizational context. By explicitly designing physical spaces for DT, organizations can legitimize its adoption, encouraging employees to step out of their comfort zones and foster innovation.

3.2. Research sample

To validate the hypotheses stated, empirical research was conducted with the Portuguese company MEO – "Serviços de Comunicações e Multimédia," hereafter referred to as MEO. MEO is a leading telecommunications company in Portugal, offering a wide range of services, including subscription television, broadband internet, fixed-line, and mobile telephony. Founded in 1991 as Portugal Telecom, the company has undergone several transformations over the years. MEO is a key player in the Portuguese telecommunications market and has significantly contributed to the growth of fiber-optic networks, while also introducing innovative services to its customers. In addition, MEO has been at the forefront of technological advancements in Portugal, expanding the fiber-optic network, launching interactive services, and developing mobile applications. The company is also involved in various social and cultural initiatives, supporting events and projects that contribute to the community and cultural development of Portugal.

The research was carried out with a commercial team of 10 employees, including their team leader. This team was chosen to enhance the information richness of our study by leveraging the specialized knowledge of the selected team members, while also addressing the practical constraint of limited availability of relevant examples within the context of the new methodology being explored.[42]

The commercial team was divided into two groups: Team Alpha and Team Beta, each consisting of five members. Team Alpha adopted DT without applying specific methods to legitimize it. In contrast, Team Beta adopted DT using specific methods to legitimize it, which will be detailed in the following sections. The purpose was to compare the results of the two teams to validate the four hypotheses.

Table 1 summarizes the characteristics of each member of Team Alpha and Team Beta, including their position in the company, years of professional experience in their current field, and years of experience at the company.

The team leader was tasked with selecting a real challenge faced by their commercial team. The challenge addressed by both Team Alpha and Team Beta was "increasing the level of knowledge of our clients' C-level executives," which involved developing personal relationships with key leaders, such as the Chief Executive Officer, Chief Financial Officer, Chief Technology Officer, and Chief Marketing Officer. This level of interaction complements existing operational contacts and allows both teams to better understand their clients' challenges and strategic directions. The teams aimed to present appropriate MEO company solutions at each stage, thereby having a greater impact on the customers' efficiency and market positioning. This strategy, in turn, would lead to a more effective commercial process with higher satisfaction, as the solutions would significantly influence the clients' businesses. Furthermore, fostering direct relationships with top organizational leaders promotes greater loyalty and attracts new businesses.

Both Team Alpha and Team Beta first participated in a conventional company theoretical workshop on creative processes and DT and facilitated by the company's Human Resource Department. This workshop was not tailored specifically for the research but was a standard session that the facilitator had previously conducted for various other teams within the organization. Further details are provided in Section 3.5.1., titled "Preliminary design thinking workshop with both teams."

Following the theoretical workshop, the next session was held exclusively with Team Alpha. Team Alpha adopted DT without implementing specific methods to legitimize it, conducting a conventional DT workshop adapted to the aforementioned challenge. This workshop was led by the company facilitator and utilized IDEO-based DT methods and tools. Further details are provided in Section 3.5.2., titled "Workshop with Team Alpha."

For the Team Beta workshop, where the objective was to address the same challenge but with the application of specific methods to legitimize DT, a preparatory workshop was conducted with the team leader. This "specific method to legitimize DT" was the ideaChef® tool, which aimed to train the team leader to facilitate the workshop with Team Beta, with technical support from the ideaChef® facilitator. A detailed explanation of the ideaChef® tool is provided in Section 3.5.4., titled "Workshop with the team leader." The primary goal was to help Team Beta foster closer relationships and a more relaxed atmosphere, increase team bonding, encourage more idea sharing, and stimulate adaptability by working outside their comfort zones. The team leader conducted the workshop and supported by the technical expertise of the ideaChef® facilitator. This session was also held in a room designed for DT. By applying specific methods to legitimize DT, Team Beta engaged in a non-conventional DT workshop adapted to the proposed

Table 1. Characterization of the teams

Team	Employee	Position in the company	Years of professional experience in the current field	Years of experience at the current company
Alpha	1	Client Manager	26	26
	2	Senior Advisor	27	17
	3	Commercial Coordinator	27	25
	4	Commercial Coordinator	24	24
	5	Account Manager	25	25
Beta	1	Commercial Manager	15	25
	2	Commercial Manager	30	35
	3	Commercial Manager	25	33
	4	Director	10	30
	5	Commercial Manager	22	22

challenge (**Section 3.5.4.** titled "Workshop with Team Beta" for further details).

3.3. Methods

The current study employed a quasi-experimental approach to investigate and compare two distinct teams: Team Alpha and Team Beta. Both teams are part of the same commercial team unit within the organization and are led by the same team leader. The central focus of this approach was to analyze the differences and similarities between the two teams regarding the outcomes of the conducted workshops. To achieve the study's objectives, the following methodological steps were implemented:

(i) Team selection and contextualization: Team Alpha and Team Beta were selected as the units of analysis due to their relevance within the organization. Both teams belong to the same group of commercial managers and share the same team leader, providing a controlled environment for comparison.

(ii) Survey development: A structured and validated survey was developed to gather relevant information on team members' perceptions of the conducted workshops. The survey scales were carefully chosen to align with the research objectives, especially given the absence of suitable existing measures for one of the hypotheses.

(iii) Workshop execution and data collection: A series of workshops were conducted over a specified period for both teams, with each session following a structured work activity. At the end of each workshop, team members were asked to complete the survey. This approach ensured data collection immediately following the workshop, minimizing potential memory biases.

(iv) Quantitative analysis: The data collected through the surveys were analyzed using appropriate statistical techniques. The quantitative analysis focused on comparing responses between the two teams, identifying trends, and assessing significant differences in participants' perceptions. Statistical tools and correlation analyses were applied as necessary.

(v) Interpretation of results: Emerging patterns and significant differences in the data were interpreted in the context of the research objectives.

(vi) Discussion and conclusions: The results were discussed in relation to relevant literature and the research objectives. Conclusions were drawn from the quantitative evidence, highlighting the study's contributions to understanding team dynamics and offering insights for the development of effective leadership and management strategies.

By employing a quantitative approach, this study aimed to generate empirically grounded insights into the differences and similarities between Team Alpha and Team Beta regarding the conducted workshops. The use of this approach allowed for an objective analysis of participants' perceptions, contributing to a deeper understanding of the factors influencing team performance and collaboration within the organizational context.

3.4. ideaChef® tool

ideaChef® is a service design method and tool that integrates creative problem-solving, DT, and gamification elements. In response to a specific challenge, teams use ideaChef® to convert ideas into actionable solutions, such as projects or prototypes. Based on past experiences, ideaChef® fosters the development of closer relationships, promotes relaxation, enhances team bonding, encourages informal idea-sharing, and stimulates adaptability by pushing participants outside of their comfort zones. In addition, it increases motivation and productivity among employees. ideaChef® is a board game that incorporates game components to engage teams in developing product or service concepts. It has been utilized in both academic and business innovation initiatives. While the tool can accommodate up to six participants, a minimum of three is required. The necessary equipment for generating a selected concept for a challenge includes a playboard, two sets of question cards, play points and tokens, individual boards, menu cards for each player, personalized sticky notes, dice, a pen, and a timer.[43] This tool was selected for this study because, unlike traditional design methods involving sticky notes, it offers a more enjoyable, stimulating, and structured ideation process. It enables teams to tackle innovation challenges through game dynamics, such as debating, voting on contributions, and combining or refining the most consensual components of the product or service development process.

3.5. Data collection

The following sections provide detailed descriptions and observations of the experiments conducted.

3.5.1. Preliminary DT workshop with both teams

Both Team Alpha and Team Beta participated in an initial conventional theoretical company training session titled *Creative Processes and DT*, which lasted for 2 days. On the first day, several participants arrived late, causing the rest of the team to work on computers, read emails, take phone calls, and attend meetings while waiting for everyone to arrive. Despite these delays, once the facilitator left the room, team members expressed their dissatisfaction with the length and timing of the training.

The facilitator, who has been delivering this theoretical training for over 20 years, is well-experienced in the field and known for open-mindedness and eagerness to continue learning.

Throughout the 2 days, a variety of topics were covered, including creativity, storytelling, and the essential components of creativity. The session also addressed and debunked common myths and barriers to critical thinking. The facilitator highlighted several obstacles to critical thinking, including fixed thinking, individual limitations, leadership constraints, organizational barriers, formal environments, the fear of judgment, oppressive surroundings, and imaginary boundaries. These barriers were grouped into four categories: (i) individual and organizational barriers (e.g., stereotypes and oppressive environments), (ii) cultural barriers (e.g., immediate criticism of new ideas), (iii) perception barriers (e.g., imaginary boundaries), and (iv) emotional barriers (e.g., fear of looking foolish).

In addition, the theoretical workshop introduced various creative thinking techniques, such as brainstorming, mind mapping, Edward de Bono's Six Thinking Hats, the Walt Disney method, and the 5W's 1H method. Regarding mind mapping, some team members shared their thoughts: "I have heard about it several times, but I don't know how to apply it," "It is a powerful tool to structure our ideas," "Working based on an individual scheme is more challenging for me," and "I am very fond of diagrams." The participants also associated DT with product development, particularly regarding the 5W's and the Walt Disney method, and viewed it as a methodology for innovation and gathering broader input. In addition, the facilitator discussed the challenges of innovation in business and highlighted the added value it brings, using examples from companies such as Napster, iTunes, and Spotify.

These topics were interspersed with videos related to the theme, bibliographic sharing, film references, case presentations, and suggestions for TED Talks. Music was played between activities, sometimes calming and ambient, other times featuring well-known pop songs. Examples of highly regarded companies and their organizational cultures, such as Google and Airbnb, were also shown. The facilitator frequently referenced quotes and stories from well-known authors, including Philip Starck, John Hockenberry, Bill Evans, Tim Brown, and Thomas Edison, to validate his message.

Throughout the training, the facilitator demonstrated confidence in his communication, maintained a strong presence, and engaged the teams with storytelling. For instance, he shared the origin of common expressions, such as "when a penny drops." He encouraged collaboration and idea sharing on every topic. During these discussions, moments of spontaneous reflection naturally emerged, including debates on whether the appropriate dress code in the commercial sector, both inside and outside of companies, is an important professional issue.

To consolidate the topics covered, the facilitator provided materials such as papers, cardboard, sticky notes, plasticine, pencils, and pens and carried out various activities. These activities included discussing an object each participant identified with, drawing on paper within a limited time, connecting nine points with only four lines, drawing the number "6" on a sheet of paper using only the Roman numeral "IX," interviewing a teammate for an empathy exercise, and doing the "three-part brain" exercise, which was a more interactive and engaging activity to push participants out of their comfort zones. The facilitator also led Tom Wujec's Marshmallow Challenge, among other exercises.

At the beginning of the theoretical workshop, many participants were preoccupied with their phones, making calls, checking emails, or replying to messages. However, over the 2 days, their interest and enthusiasm for the topic grew. The group began asking numerous questions, critically engaging with the facilitator's points, and analyzing one another's opinions. A few participants stood out for asking particularly insightful questions and demonstrating significant interest.

The atmosphere in the room was relaxed, with participants conversing calmly, naturally sharing ideas, and exchanging knowledge and curiosities. Occasionally, there was some side chatter, accompanied by the noise of people fiddling with their bags and phones ringing.

During breaks, participants drank coffee with the facilitator and continued exchanging ideas outside the training space, which was an interesting aspect of the theoretical workshop. Overall, the group remained fun and collaborative while being receptive to the exercises. However, there were moments when participants struggled to disconnect from work, often remaining on standby for work-related matters. One individual consistently took a leadership role, while another was initially apprehensive or had difficulty understanding the exercises. Statements such as "I am not able to fit into this thinking, I have difficulty understanding the exercise," "At first, I had more difficulty understanding, and I was more apprehensive," and "I found this process much more interesting than the others," were shared. One participant remarked, "I think this process is complementary and helps consolidate the other knowledge and methods," and another said, "I think it is great to be forced out of your comfort zone."

By the end of the day, the group was visibly tired but remained open to listening and learning. On the 2nd day, participants became more dispersed, having become more accessible and at ease. Throughout the training, the group frequently sought the facilitator's assistance with questions. It was evident that, toward the end of the theoretical workshop, some participants were growing impatient to finish the activities and conclude the training day.

The room lacked natural light and was closed off. The chairs were arranged in a semicircle to promote interaction and provide good proximity to the facilitator. There were many cables and devices on display, contributing to some clutter. The facilitator had brought all the materials in a suitcase, which was placed on a table in an open corner for everyone to see.

During the theoretical training sessions over the 2 days, some participants voiced complaints about the environment, including remarks such as: "A whole day spent in here," "The white lights are tiring," "These chairs are not comfortable for sleeping," "This environment feels a bit claustrophobic, it suffocates me," and "It was very noisy."

3.5.2. Workshop with team alpha

Initially, the facilitator faced some difficulties in understanding the challenge presented by the manager. However, he was very cooperative and organized the workshop accordingly.

Team Alpha's practical workshop was held the morning after the company's theoretical workshop. The facilitator welcomed the participants with quiet background music as they entered the room. On this morning, a more subdued atmosphere prevailed compared to the theoretical sessions held over the previous 2 days.

After presenting the challenge, Team Alpha initially responded with heavy breathing and appeared slightly withdrawn. However, they soon became engaged and recognized the challenge as something they needed to overcome: "it is complicated to get customers to share their needs. We also conduct surveys, but extracting their actual needs from that is very difficult."

The first step was brainstorming: individual ideation in silence, with one idea per sticky note. The team gathered at a table, working silently with background music. They felt more comfortable with the brainstorming process, as they had already practiced it the day before. Following this, the group shared their ideas, which quickly led to a more serious debate. During this discussion, the team aired their professional frustrations, and ideation flowed freely as they addressed real problems drawn from their professional experiences.

Finally, each participant placed their sticky notes on the wall, arranging them in an Effort Matrix. The group debated the position of each sticky note/idea. In this rich, intense, and extensive debate, they shared various perspectives, which sparked even more ideas. These new ideas were added to the matrix and organized into clusters. One member of Team Alpha, who had been more reserved during the previous days and had not contributed as much, became more collaborative and engaged. Overall, all team members contributed with more commitment during this workshop.

The final step involved selecting one of the clusters to focus on. They applied the 5 W's and 1 H tools for individual reflection before discussing everyone's ideas. At this stage, the group was highly focused.

It was noticeable that the team naturally used DT terms such as "diverge," "converge," and "share ideas without judgment." They were also committed to making their solution a reality as they delved deeply into the topic. At the end of the workshop, the group shared some feedback: "unfortunately, what happens with these trainings is that, as much as we want to implement DT daily, we think, tomorrow we can try it next week we can try it... but then, at work, we have to focus on individual tasks. For example, the mental part is the brainstorming process, where we work individually on our own ideas." "It's a new way of thinking. It's a much more organized approach, with a process already in place. The exercise of deconstructing our preconceptions and coming up with a solution to the problem identified by the manager is invaluable." "This is a great methodology. I'm thrilled that I came here." "We need to force ourselves to do these things regularly so that they become part of our routine and finding solutions to our challenges becomes automatic," said the team leader.

3.5.3. Workshop with team beta leader

Team Beta coordinator demonstrated strong leadership qualities, showing confidence and a keen interest in the topic under study. He was open to the ideaChef® tool and committed to learning how to facilitate the workshop. However, he requested technical support related to the tool while conducting the workshop with Team Beta.

3.5.4. Workshop with team beta

The workshop with Team Beta was held outside MEO in a room adapted for training in a co-working space. This room is notable for its spaciousness, natural light, and garden space. Half of the team, along with the team leader and the ideaChef® facilitator, attended the workshop. The team leader's first impression of the space was, "It's different from usual." Initially, the team leader framed the problem to be addressed: how to increase the C-level. His team clearly understood the explanation, and the leader was very comfortable and relaxed while presenting the challenge. He also referenced other institutions, such as Politecnico di Milano, that have previously applied the ideaChef® tool to innovation challenges.

Next, two minutes were allotted for individual brainstorming, during which each participant wrote down as many ideas as possible on a piece of paper to increase the C-level. After the brainstorming session, the team presented their ideas to the team leader, who recorded them on a single sheet of paper. The team was focused, sitting around the table, and appeared very engaged in the collaborative process. Following the brainstorming, the team leader asked everyone to group their ideas into clusters. The team naturally got up and analyzed all the ideas around the table. At times, the team leader sought support from the ideaChef® facilitator for more technical guidance related to the tool. In the next step, the team selected their best idea and wrote it in a tweet-length format, i.e., in just a few characters. The team was very comfortable with this activity, and there were moments of laughter.

After the idea was selected, the ideaChef® facilitator set up the board on the table and, along with the team leader, distributed materials to the team members. The facilitator provided a brief technical introduction to how the tool works. The team showed interest, asking questions, and the team leader offered compliments. Once the explanation was complete, ambient music was played, and the team rolled the dice to begin the game. The team members were highly involved and invested in the challenge alongside the team leader, as they shared different perspectives in vibrant debates. "The team's thinking throughout the development of ideaChef® was not only focused on solving the challenge but also on achieving the goals related to their roles in the company, particularly the commercial aspect – how they could apply this new way of thinking in their daily work as salespeople. This was an interesting perspective," noted the team leader. After the first three rounds of ideaChef®, the group took a coffee-break in an outdoor space separate from the workshop room.

Following the coffee break, there was a reset moment where the ideaChef® facilitator challenged the team to converge and focus on a more detailed and specific solution. The team was enthusiastic and quickly contributed numerous ideas. In the subsequent steps, they remained focused on refining the solution. As the game progressed, the rules shifted slightly to emphasize the "main course" cards, which helped structure the ideas more effectively and quickly.

3.6. Measures

To validate Hypothesis 1, "Organizations require creative trust," questions related to performance evaluation (PE) were used, consisting of five items on a Likert-type scale. Although Hofstede's power distance scale already existed,[44] we argue that the Power Distance scale is broader and more applicable in terms of cultural and cross-cultural aspects. In contrast, this study focuses on understanding how the specific relationship between leaders and subordinates affects the adoption of practices such as PE. This approach captures concrete perceptions and behaviors within this specific organizational context. The use of PE-related questions to measure power distance aims to indirectly assess the power dynamics and the extent of authority in employee-manager relationships. By measuring employees' perceptions of their involvement in these processes, we gain insights into the power dynamics within the organization.[44,45] Higher scores on these questions might suggest a more inclusive and participatory culture, which, according to the hypothesis, can contribute to legitimizing and adopting DT practices.

The Van Dyne and LePine Voice Scale[46] was used to validate Hypothesis 2, "Companies need to create a culture of openness and feedback." This measurement evaluates employees' propensity to speak out and express their thoughts at work. It is frequently utilized in research to assess the connection between speech behavior and outcomes, including work satisfaction, creativity, and performance. The scale has been adapted for use in multiple languages and cultures and has demonstrated reliability and validity in various contexts.[46]

A total of five items were used on a Likert-type scale where 1 corresponds to "very poor" and 5 corresponds to "very good."

The Empowering Leadership Questionnaire[47] was used to quantify empowering leadership practices in the workplace and validate Hypothesis 3: "organizations need leaders trained in DT." This scale has been employed in various contexts to evaluate empowering leadership behaviors and has demonstrated strong reliability and validity. Researchers and practitioners can use it to assess empowered leadership behaviors and their effects on employee outcomes, such as work satisfaction, motivation, and performance.[47] A total of seven items were used on a Likert-type scale where 1 corresponds to "never" and 7 corresponds to "always."

To validate Hypothesis 4: "organizations need a physical space designed specifically for the use of DT," there is, to our knowledge, no existing scale to quantify the influence of the workplace. Although the workplace effect was not formally measured, research by West and Wind[41] concluded that the environment had a significant impact on business outcomes. After relocating to its new headquarters, the company's financial performance surged, with earnings increasing by 40% annually from 1996 to 2001, while maintaining the same personnel size. Since the relocation, its average yearly return has been 28%. A workplace design that aligns with the company's values and culture can provide many benefits, contributing to ongoing innovation, growth, and the achievement of business goals. Therefore, this scale will be developed using the three principles of West and Wind[41] – (i) embrace the culture: a company's culture should be reflected in its workplace design. It is crucial to align workplace design with the organization's culture and values. Companies cannot make changes to the workplace without also evolving the culture and expecting positive outcomes. Solutions will vary greatly, as each culture is unique. (ii) Fiscal responsibility: organizations should avoid the "edifice complex," a tendency in some companies to waste money on extravagant displays. (iii) Build for flexibility: flexibility should extend beyond just interior areas.[41] A total of four items were used, on a Likert-type scale where 1 corresponds to "not suitable at all" and 5 corresponds to "very suitable."

In Table 2, the items are organized and grouped into four thematic categories, and the corresponding descriptive statistics are provided for each item.

3.7. Data analysis

The hypothesis tests were formulated based on summated scales, corresponding to the average score of the measures associated with each construct under analysis (power distance, leadership, culture, and physical space).

Given the small sample size (N = 10), the hypotheses that Team Beta scores higher than Team Alpha on the four dimensions of DT legitimacy were evaluated using the

Table 2. Items and descriptive statistics

Constructs and items	Min	Max	Mean	SD
Power distance	3.400	4.400	3.880	0.270
PD1: My Performance Evaluation helped me identify my strengths and weaknesses in relation to my work.	4	5	4.200	0.422
PD2: My Performance Evaluation helped me improve my job performance.	3	5	4.000	0.471
PD3: My Performance Evaluation helped me identify my training and personal development needs.	3	5	4.100	0.568
PD4: My Performance Evaluation aided in my career development and planning.	2	4	3.300	0.675
PD5: My Performance Evaluation, in conjunction with my management, helped align clear performance criteria for the next year.	3	4	3.800	0.422
Leadership	3.200	5.000	4.100	0.655
LD1: How good is your management's leadership ability?	3	5	4.10	0.738
LD2: How good is your management at following the decisions made?	2	5	3.80	0.919
LD3: How good is your management at monitoring the results of actions taken?	3	5	4.00	0.816
LD4: How good is your communication with your management?	3	5	4.00	0.667
LD5: How comfortable are you expressing your opinions and disagreeing with your immediate management?	4	5	4.60	0.516
Culture	2.710	5.860	4.557	0.953
CU1: During the workshop, how often did you make suggestions on issues impacting this workgroup?	3	7	5.70	1.252
CU2: During the workshop, how often did you communicate your opinions to colleagues in this group, even if your opinion differed from others?	5	7	6.30	0.675
CU3: During the workshop, how often did you feel afraid to express disagreement with the workshop moderator?	1	3	1.30	0.675
CU4: During the workshop, how often did team leader make recommendations on issues affecting this workgroup?	1	6	3.10	2.234
CU5: During the workshop, how often did you speak up and encourage the team?	4	7	5.20	0.919
CU6: During the workshop, how often did the team leader speak up and encourage the team?	1	7	5.20	2.098
CU7: During the workshop, how often did you contribute to the team with ideas for new projects or changes?	3	7	5.10	1.449
Physical space	2.000	5.000	3.625	1.069
PS1: In your opinion, how suitable is the physical space for facilitating the workshop?	2	5	4.00	1.054
PS2: In your opinion, how suitable is the physical space for creating a relaxed environment?	2	5	3.50	1.354
PS3: In your opinion, how suitable is the physical space for generating new ideas?	2	5	3.50	1.269
PS4: In your opinion, how suitable is the physical space in relation to aspects that characterize the company's culture?	2	5	3.50	0.972

Abbreviations: CU: Culture; LD: Leadership; Max: Maximum; Min: Minimum; PD: Power distance; PS: Physical space; SD: Standard deviation.

Wilcoxon–Mann–Whitney non-parametric test for two independent samples.[48] Statistical analyses were performed using IBM SPSS Statistics software, version 28, with $\alpha = 0.05$. As this software version of the software does not calculate the effect size for the Wilcoxon–Mann–Whitney test, we manually computed the effect size using the formula presented by Marôco.[49]

4. Results

Table 3 presents the results of the Wilcoxon–Mann–Whitney non-parametric test for all research hypotheses. According to the results, only the dimension of physical space showed statistically significant differences between the two teams. Although Team Beta's scores were higher than Team Alpha on all other dimensions, these differences were not statistically significant.

Hypothesis 1 aimed to promote closer relationships, relaxation, increased bonding among team members, more idea sharing in a more informal environment, stimulate adaptability in activities outside one's comfort zone, and foster greater motivation and productivity among employees. The results showed that Team Beta scored higher than Team Alpha (MRBETA = 5.70; MRALPHA = 5.30), but the observed differences are not statistically significant (U = 13.500; pU = 0.429; N = 10, d = -0.080). Figure 1 illustrates the distribution of scores for the two teams.

This outcome suggests that Team Beta had higher scores than Team Alpha. However, this difference could be due to chance variation rather than a true reflection of any systematic or meaningful distinction between the two teams. Therefore, it is not possible to confidently conclude that the observed differences are attributable to the variables studied, as opposed to random noise. A limitation in comparing Team Alpha and Team Beta is the time gap between the theoretical training and the practical workshop. Team Alpha held the workshop the day after the theoretical training, which may have provided greater continuity and a stronger connection between the concepts learned and their practical application. This workshop timing allowed Team Alpha to maintain momentum and enthusiasm during the theoretical training, potentially enhancing their ability to adopt and implement DT more effectively. On the other hand, Team Beta had a 2-week gap between the theoretical training and the practical workshop, which may have led to a disconnect between theory and practice. This gap in time could have resulted in a loss of enthusiasm, interest, and even some forgetting of key concepts.

The aim of Hypothesis 2 was to empower employees to speak up and build trust, thereby increasing their focus on work. This increase in productivity occurs when employees feel heard while expressing their opinions, which leads to a decrease in negative attitudes and an increase in happiness

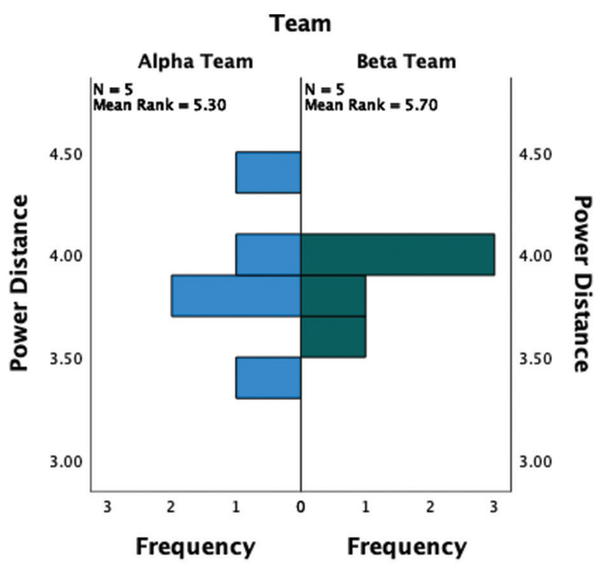

Figure 1. Mean ranks and scores for the power distance construct

Table 3. Results of the Wilcoxon-Mann-Whitney test for the dimensions of design thinking legitimacy

Dimension	Team	*N*	Mean rank	Sum of ranks	Mann-Whitney U	Exact *P*-value (1-tailed)	Effect dimension
Power distance	Alpha	5	5.300	26.500	11.500	0.429	−0.080
	Beta	5	5.700	28.500			
Leadership	Alpha	5	5.000	25.000	10.000	0.357	−0.200
	Beta	5	6.000	30.000			
Culture	Alpha	5	5.400	27.000	12.000	0.500	−0.040
	Beta	5	5.600	28.000			
Physical space	Alpha	5	3.000	15.000	0.000	0.004*	−1.000
	Beta	5	8.000	40.000			

Note: *Indicates that the difference is significant at the 0.05 level.

in the workplace. The results indicated that Team Beta scored higher than Team Alpha (MRBETA = 6.00; MRALPHA = 5.00), but the observed differences were not statistically significant (U = 10.000; pU = 0.357; *N* = 10, d = -0.200). Figure 2 illustrates the distribution of scores for the two teams.

This outcome suggests that although Team Beta had higher scores than Team Alpha, this difference may be due to chance variation rather than a true reflection of any systematic or meaningful distinction between the teams. It is not possible to confidently conclude that the observed differences were attributed to the variables under study, rather than to random noise.

The aim of Hypothesis 3 was to compare the experience of a standard DT moderator conducting a DT workshop versus the direct team leader facilitating the workshop to solve the team-specific problem, introduce a new tool, and guide the team through new concepts. This hypothesis aimed to confirm that having managers trained in DT legitimizes its adoption. The results showed that Team Beta scored higher than Team Alpha (MRBETA = 5.60; MRALPHA = 5.40), but the observed differences were not statistically significant (U = 12.000; pU = 0.500; *N* = 10, d = -0.040). Figure 3 illustrates the distribution of scores for the two teams.

This outcome indicates that while Team Beta had higher scores than Team Alpha, the difference could be attributed to chance variation rather than a true, meaningful distinction between the teams. Therefore, it is impossible to confidently conclude that the observed differences are the result of the variables under study, as opposed to random noise. The leadership characteristics and skills of the team manager can significantly influence results. A leader with an open mindset who values innovation encourages creative thinking and promotes experimentation can foster a culture that supports adopting innovative approaches such as DT. Conversely, a more conservative leader, who values compliance and conventional efficiency, may discourage the exploration of new approaches, potentially limiting the team's ability to innovate.

The aim of Hypothesis 4 was to contribute to the legitimization of DT adoption by reorganizing the physical space in the company to incorporate specific characteristics that support DT practices. Team Beta scored higher than Team Alpha (MRBETA = 8.00; MRALPHA = 3.00), and the observed differences were statistically significant (U = 0.000; pU = 0.004; *N* = 10, d = -1.000). Figure 4 illustrates the distribution of scores for the two teams.

This outcome validates the hypothesis and suggests that a dedicated physical space for DT activities influenced the teams' perception and adoption of DT practices. The space used by Team Beta would ideally include additional features such as a more flexible work environment, in a newly built space distinct from typical offices, with writable walls and moveable furniture. However, due to constraints of time, budget, and available venues to facilitate the workshop, it was not possible to meet all of these ideal conditions. Future research could explore the specific aspects of the physical space that contributed most to its impact, as well as investigate whether variations in the design of such spaces could yield different outcomes.

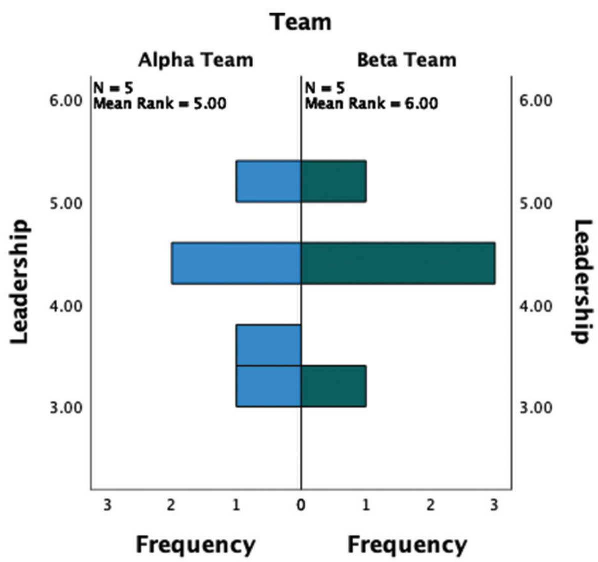

Figure 2. Mean ranks and scores for the leadership construct

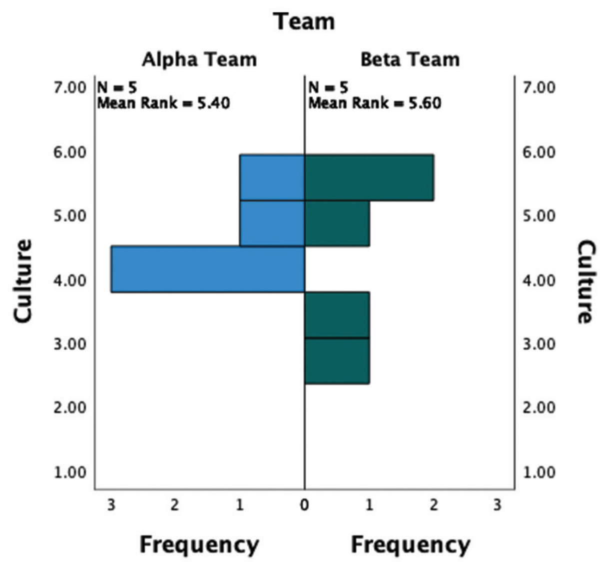

Figure 3. Mean ranks and scores for the culture construct

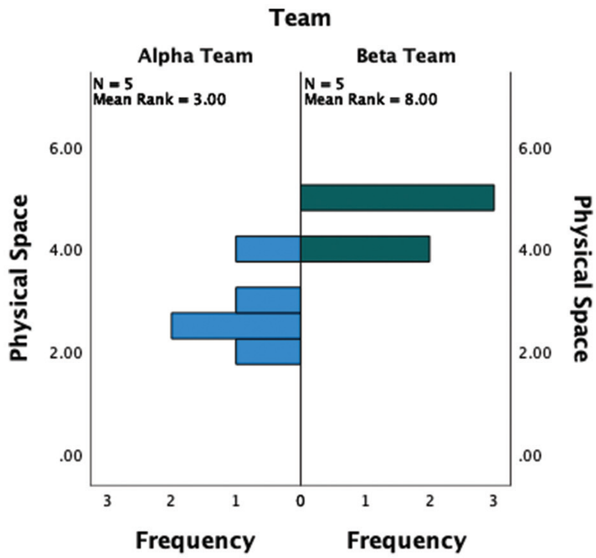

Figure 4. Mean ranks and scores for the physical space construct

5. Conclusion

This paper contributes to the study of legitimacy challenges in the implementation of DT by characterizing the values and culture associated with DT.[16,37] Despite the growing interest in DT among practitioners, limited research has been conducted on how companies practically apply DT,[1] and there is still a minimal understanding of the actions that managers take to facilitate DT adoption within organizations.[13]

This study addressed a significant conceptual and empirical gap in the literature on DT adoption, i.e., the need for greater legitimacy. It explored why legitimacy is a critical barrier to DT adoption in organizations and proposes a set of hypotheses to overcome this challenge. By drawing on employee perceptions and organizational workplace theories, this research provides actionable insights for legitimizing DT within companies. Design interventions can raise awareness, promote interest, foster motivation, and guide design activities within an organization. The developed hypothesis integrates validity and reliability approaches to better understand the underlying interpersonal processes that contribute most effectively to holistic innovation.

The study highlights the importance of factors such as confidence in creativity, a culture of openness, leadership training in DT, and the creation of a dedicated physical space. These factors are shown to play a critical role in the successful adoption and implementation of DT within organizations.

The results indicated that Team Beta had higher scores than Team Alpha in relation to Hypothesis 1. However, it was not possible to confidently conclude that the observed differences were attributable to the variables under study, as opposed to random variation. Although no statistically significant differences were found between Team Alpha and Team Beta across several hypotheses, Hypothesis 1 suggests that both teams demonstrate similar levels of confidence in creativity, which may indicate that they both recognize the importance of creativity within their work context. As such, this finding suggests that both teams are open to exploring creative approaches, even if the differences have not been statistically validated.

Regarding Hypothesis 2, the results indicated that Team Beta had higher scores than Team Alpha; however, it was not possible to confidently conclude that the observed differences were due to the studied variables rather than random variation. Although no statistically significant difference was found in the culture of openness and feedback between the two teams, this finding emphasizes the importance of fostering a culture that supports innovation and the exchange of feedback. Even in the absence of statistically significant differences, the value of promoting an organizational culture that encourages open communication and idea-sharing remains clear. In addition, observations of participants stepping outside their comfort zones and engaging in meaningful debates suggest that DT activities can challenge organizational norms and stimulate critical reflection, ultimately contributing to a more dynamic and innovative work environment. Comments regarding the difficulty of brainstorming individually underscore the importance of collaborative environments in fostering creativity, reinforcing the idea that collaboration is essential to the innovation process. Furthermore, observations highlighting the need for regular practice of DT activities to make them automatically emphasize the importance of consistency in incorporating DT into daily work. These insights reinforce the relevance of DT in organizations and point to areas that warrant further exploration to promote a culture of innovation and creativity.

Regarding Hypothesis 3, the results showed that Team Beta had higher scores than Team Alpha. However, it was not possible to confidently conclude that the observed differences were due to the variables studied rather than random noise. While the results were not statistically significant, this does not determine the importance of providing DT training for leaders. Such training can foster an environment that is more conducive to innovation and creativity. The finding suggests that leaders involved in DT activities can positively influence collaboration and the generation of creative ideas within their teams. In addition, participants' comments about the difficulty of integrating DT practices into their work routines highlight the need for strategies that facilitate the continuous implementation of DT in the organizational context. This awareness can drive efforts to develop more effective integration methods.

Regarding Hypothesis 4, this paper confirms that having a physical space specifically designed for DT activities can positively influence the perception and adoption of DT practices by teams. This hypothesis was the only one where the results were statistically significant, indicating that a dedicated physical space had a positive impact on the perception and adoption of DT practices. This finding underscores the importance of investing in physical environments that support DT activities, providing a clear strategy for promoting DT within organizations. It also highlights the relevance of creating suitable physical spaces that foster creativity and innovation in companies.

Overall, the legitimacy of adopting DT within organizations can be achieved through a combination of factors: increasing creative confidence, promoting a culture of openness and feedback, providing leadership training in DT, and creating a dedicated physical space for DT. While the study did not conclusively prove differences in creative confidence between the teams, it is evident that both teams recognized the importance of creativity. Encouraging employees to explore creative approaches – regardless of whether statistically significant differences are observed – can foster a more innovative work environment. Fostering a culture that encourages openness to innovation and feedback is essential. Although the study did not find statistically significant differences in the culture between teams, it highlights the importance of creating an environment where open communication and the exchange of ideas are actively encouraged. Having leaders trained in DT is crucial. Leaders who understand and support creative and problem-solving approaches can positively influence collaboration, idea generation, and the overall adoption of DT within their teams. Finally, the presence of a dedicated physical space designed for DT activities has a significant impact on the perception and adoption of DT practices by teams. Investing in such a space can tangibly demonstrate the organization's commitment to innovation and creativity. By addressing these factors collectively, organizations can work toward legitimizing the adoption of DT both on individual and social levels within their structures. This holistic approach acknowledges the importance of physical resources, leadership support, cultural values, and individual creative confidence in successfully integrating DT practices into the organization.

The paper makes a significant contribution to both theory and practice in the context of organizational DT adoption. One of the notable contributions is the development of hypotheses that integrate validity and reliability approaches, allowing for a deeper understanding of the interpersonal processes that play a critical role in holistic innovation. In terms of practical implications, the paper offers valuable insights for companies seeking to innovate and enhance competitiveness. It underscores the importance of DT in fostering innovation and suggests that organizations aiming to remain competitive can benefit from its findings. While some statistical significance was not achieved for specific hypotheses, the study highlights the importance of fostering creativity, cultivating an open culture, providing leadership training, and creating dedicated physical spaces for DT activities. To sum up, this paper provides a strong foundation for future research in DT adoption and its impact on innovation and organizational performance.

Future research opportunities include extending this study to small- and medium-sized businesses to explore how organizational culture, organizational climate, employee–supervisor relationships, and workplace environments influence DT adoption. Comparative studies across different countries could provide insights into cross-cultural variations in DT adoption. Furthermore, in-depth research into the link between employee attitudes, beliefs, and emotions and the success of DT implementation is essential. Emphasizing the role of empathy, as Elsbach and Stigliani[50] highlighted, future research should examine how empathy contributes to organizational cultural values of collaboration and user focus. It should also consider these aspects from an individual perspective and explore the micro-foundations of DT.

5.1. Contributions to theory and practice

This paper contributes to the development of more robust approaches for advancing methods and processes for DT adoption in organizations. Companies aiming to innovate and become more competitive will benefit from the findings of this research. Innovation is essential to the construction and evolution of brands seeking to stand out in the market, with DT playing a pivotal role in this process. In addition, this study increases the visibility of DT in various business sectors, leading to better-informed professionals.

This research also aimed to provide essential insights into the validity of DT in organizations. It offered a solid theoretical foundation to address the adoption of DT in organizations, exploring several dimensions that influence its legitimacy, including national culture, organizational climate, the quality of relationships between employees and supervisors, and the organizational environment. This study contributes to answering the question of which factors affect the acceptance and adoption of DT.

Beyond its contribution to DT theory and innovation management, this paper advances knowledge in the management of innovation teams, innovation culture, and organizational leadership. By examining the factors influencing the successful adoption of DT, this research sheds light on broader principles that can foster innovation in organizations. It highlights the importance of cultivating a culture of openness and feedback, providing training for leaders in creative problem-solving approaches, and creating physical spaces dedicated to innovation activities. These insights not only benefit DT adoption but also enhance the overall innovation ecosystem within companies, driving them to be more competitive and adaptable in an ever-evolving market. Furthermore, the research underscores the vital role of employee perceptions and interpersonal processes in fostering innovation, making it a valuable resource for organizations striving to stay at the forefront of creative exploration.

This paper also aids companies in establishing legitimacy in the adoption of DT within innovation teams. As an innovation strategy, it supports the diversification of offerings, the development of increased know-how in DT, and the creation of better-informed professionals. Moreover, it contributes to value creation for customers by helping organizations better understand their needs and generate innovative, differentiated solutions in the market. It also facilitates the development of more effective plans to reach defined goals, fosters the creation of a learning environment, and promotes rapid problem-solving, all of which encourage creativity and differentiate companies from competitors. The results can be applied during the initial stage of developing new products or services and during the commercialization of existing products.

In addition to the contributions mentioned above, it is essential to emphasize that the increased legitimacy of DT within an organization can foster greater engagement from teams throughout the entire innovation cycle. When DT is widely recognized and accepted as a valuable strategy, teams are more likely to embrace it enthusiastically – from the early stages of idea generation to the development of new products or services and even during the commercialization process. This heightened engagement can foster a continuous culture of innovation, where teams are motivated to explore creative solutions, address challenges with agility, and distinguish themselves from competitors. Ultimately, the increased legitimacy of DT acts as a catalyst for creating a dynamic and innovative organizational environment, consistently generating unique and customer-centric solutions that position the company as a leader in its industry.

5.2. Limitations and research opportunities

This study has several limitations, primarily related to the sample size. A larger sample size would improve the statistical power of the study, enhancing the ability to detect significant differences and trends. By incorporating these suggestions into future study designs, researchers can mitigate limitations and improve the reliability, validity, and generalizability of findings related to the adoption of DT in organizations.

Another limitation was the limited time available to conduct the study and monitor the team, which had scheduling constraints. To address this, reducing the time gap between theoretical training and practical workshops for all teams could help maintain the momentum and enthusiasm generated during the training, leading to more effective implementation of DT principles. Furthermore, providing leadership training for team managers on how to foster innovation, open-mindedness, and a growth mindset, as well as an in-depth introduction to the ideaChef® tool, could help mitigate the impact of varying leadership characteristics on the team's adoption of DT. Extending the duration of workshops for both teams would ensure they have sufficient time to understand, internalize, and apply DT concepts. This would help reduce potential biases introduced by differing workshop lengths and allow teams to better explore and adopt DT practices. Moreover, conducting longitudinal studies that track teams over a longer period would help capture changes and improvements in the adoption of DT practices over time, reducing the potential disconnect between theory and practice. In addition, using a combination of quantitative and qualitative data collection methods could provide deeper insights into the factors influencing the adoption of DT, thereby addressing some of the limitations of the current study.

Finally, the sample could have been more diverse. Aiming for diversity in terms of age, experience, personality traits, and mindset would provide a richer and more comprehensive understanding of the impact of DT adoption.

The study opens new avenues for further investigation. A detailed evaluation of the performance of DT projects is necessary to develop metrics for improving adoption. Future research should address the need for more success indicators for DT. How do organizations collect data or indicators that demonstrate DT's successful adoption? What types of indicators can be used to measure this? Establishing a meaningful system of indicators is crucial from both academic and managerial perspectives.

This research focuses on the legitimacy of DT adoption in large organizations and their workplace environments.

MEO, as part of a multinational organization with established innovation processes and a long history of DT, serves as a case study. Future research could explore small- and medium-sized businesses' national culture, organizational climate, relationship quality between employees and supervisors, and workplace settings. It would also be valuable to compare organizations across different countries.

Furthermore, the relationship between professional qualifications, employees' attitudes, beliefs, and emotions, and DT success warrants further investigation. Elsbach and Stigliani[50] highlighted the role of empathy in DT, describing it as "an important signal of organizational cultural values of collaboration and user focus." Future research should consider the individual perspective, contributing to the literature on DT and micro-foundations. More research is needed on the micro-foundational aspects of DT to better understand the connections between people, processes, and structures.

This research demonstrates that macrolevel national culture, mesolevel organizational climate, micro-level relationship quality between employees and supervisors, and views on organizational workplace all contribute to a better understanding of DT legitimacy. Moreover, it complements an emerging stream in innovation and design management research, revealing that corporate DT behavior is often best explained at the microlevel of analysis.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Mariana Passadouro, Rui Patrício
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Investigation: Mariana Passadouro, Rui Patrício
Methodology: All authors
Writing – original draft: Mariana Passadouro
Writing – review & editing: Mariana Passadouro, Rui Patrício

Ethics approval and consent to participate

Consent to participate was obtained from all participants involved in the study. Written data were collected through observations, and participants also filled out questionnaires anonymously.

Consent for publication

Consent for publication was obtained from all participants involved in the study.

Availability of data

The data used in this study can be accessed upon request by emailing the corresponding author.

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ARTICLE

Rating the importance of material selection and sustainability criteria in building material selection

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Abstract

Material selection is one of the most critical steps in constructing a building that is safe, economical, esthetically pleasing, durable, and functional, and ensuring building sustainability has become an indispensable task nowadays. Multiple options are available for people interested in owning their own residential property: (1) Purchasing finished houses; (2) building their own houses, which entails selection and purchase of building materials; and (3) purchasing unfinished houses and carrying out large-scale renovations. In this study, a survey with 141 participants was conducted to identify the extent of importance our respondents attach to 11 material selection criteria and seven sustainability criteria for building material selection. The survey data were subjected to descriptive and inferential analyses, which revealed no significant difference in the participants' opinions according to their demographic characteristics. Thus, the results were generalized by determining the relative importance of the criteria. Durability and availability of materials and availability of skilled labor force were identified as the most important material selection criteria. Durability, ease of maintenance, and energy efficiency were determined as the most important sustainability criteria. Although cost is viewed as one of the obstacles to sustainable building construction, more than half of the participants stated that they could bear an additional cost ranging from 5% to 15% for sustainable materials. By comprehensively depicting the perspective of non-professionals, the results of this study provide a crucial reference for the stakeholders of the construction industry.

Keywords: Building material; Inferential analysis; Relative importance; Sustainability

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1. Introduction

At its core, people expect a building to be safe, economical, esthetically pleasing, durable, and functional. In addition to these, sustainability is also indispensable nowadays. To meet all these criteria, the right project must be executed using the right materials and workmanship. In this respect, material selection is critical in meeting these requirements of a building. However, the use of hundreds of different materials and products in the construction of buildings makes material selection a complex process.

This complex process is an important task for designers, contractors, and users. To achieve what is expected of the building, material selection is also directly related to the concepts of time, cost, and quality, which determine the success of a project.[1] Stakeholders try to select the best-performing materials based on their mechanical, functional, and physical properties.[2,3] This is where the cost comes into play. Various materials on the market perform the same function but have very different initial costs. However, materials with low initial cost may, due to their poor quality, degrade with time, necessitating replacement within a short span of usage. Therefore, the materials' durability against use and various environmental conditions such as moisture and corrosion are also important criteria. Naturally, every user prefers the material that will serve for the longest time without losing its qualities in the conditions it will be used in. This is important both in terms of avoiding additional costs for maintenance, repair, and renewal and in terms of the material not losing its function and esthetics during use.

With globalization and the use of technology, it has become possible to see and examine different materials produced worldwide. Although various building materials produced in distant places may be attractive to users in terms of various aspects, especially their esthetic properties, choosing such materials is both more costly and may cause possible disruptions, especially those requiring transportation, causing significant disruption to the construction schedule. In this respect, choosing easily available and local materials is often more favorable to the construction budget and schedule. Nevertheless, for some users, esthetic concerns are more important, and they may order custom-made ceramics from Italy for a house they are building in Australia, for example, despite all kinds of risks. Although esthetics may not be so important for every user, it is one of the indispensable conditions that a building must meet. Tastes vary, but human nature loves beauty, and no one wants the buildings they spend most of their lives in to be ugly. As each material is esthetically pleasing in its distinct way, the manufacturing process of a building could differ from others. Higher technical expertise, more time and labor are required to make certain materials, while others can be manufactured more easily. Therefore, tight schedules and cost pressure in a project can influence material selection decisions. In addition to the material's maintenance cost, ease of maintenance is also an important factor. Easy maintenance of materials that are damaged due to usage conditions and environmental conditions or that require routine maintenance is of critical importance. For example, if glass is used on a building's exterior, the facade needs to be routinely cleaned and the owner needs to bear the cost and workload involved in the maintenance process.

As can be observed, there are numerous criteria to consider when choosing materials. Furthermore, all of these criteria often conflict with each other and the selection of the best material for one criterion may require disregarding other criteria.[2] As mentioned, a material with a high initial cost can be used for many years without significant maintenance costs thanks to its durability and can compensate for its high initial cost. Again, the fact that a popular material with high esthetic properties requires qualified labor may cause the cost to increase, the project to be delayed, or the application not to be of the desired quality. Ultimately, stakeholders involved in material selection must find the optimum solution.

While the search for the optimum solution has probably been an ongoing process since ancient humans built structures for shelter, the process has become much more complex in the past few centuries with the growing diversity of materials owing to the development of ceramics, metals, alloys, and polymers. This complexity has been further increased in this century with the emergence of the necessity to adapt the concept of sustainability to the process. Sustainability addresses various environmental, economic, and social issues, including pollution, overconsumption, inequality, and poverty, which the world is currently facing. The sustainable development concept, which was developed in the face of the rapid depletion of natural resources and the continuous increase in pressure on the environment, is defined as development that meets the needs of current generations without compromising the needs of future generations.[4] By 2056, it is estimated that global economic activity will increase by five-fold, global population will increase by over 50%, global energy consumption will nearly triple, and global production activity will at least triple,[5] increasingly emphasizing the importance of sustainability.

The construction sector is one of the leading sectors that focuses on sustainability. This is because the sector has major negative impacts on the environment through material and energy consumption and waste generation throughout its lifecycle of design, construction, use, and demolition. Bricks, clay, stone, cement, gravel, paint, sand, and wood are among the primary building materials used in the construction sector. The continuous and intensive use of these materials consumes natural resources and causes significant damage to the environment.[6] For example, the construction sector is responsible for about 40% of the total primary energy consumption in the European Union.[7] Buildings consume large amounts of energy during construction and use. Climate change due to energy consumption and the production of chlorofluorocarbons (CFCs) is also a critical problem.[8] Buildings are also responsible for about 16% of freshwater consumption and 25% of wood consumption on a global scale and for 25% of the production of ozone-depleting CFCs using building materials and air conditioning.[9] Aside from being highly energy-consuming, buildings also have a close relationship with environmental pollution and directly affect the health and comfort of users.[10,11] All of these issues have led the sector to become one of the important application areas of sustainability, requiring the sector stakeholders to control and correct the environmental harm due to their activities.

To reduce environmental impacts in sustainable building construction, the correct selection of building materials is important.[12] Research shows that the choice of building materials is one of the important factors that can affect the sustainability of a building project.[13-15] For example, the selection of appropriate construction materials can reduce CO_2 emissions by up to 30%.[16] Conversely, choosing inappropriate materials leads to ineffective sustainability in construction and negatively affects the economic, environmental, and social aspects of buildings.[17-19] Consequently, cautious selection of sustainable materials has been identified as the easiest way for designers to start incorporating sustainable principles into building projects.[20] However, while building material selection is a challenging and complex process, the selection of sustainable materials makes it even more difficult. According to Kibert,[21] one of the most challenging aspects of a construction project is choosing sustainable materials.

In the literature, there are many studies on material selection in general and sustainable material selection in particular, conducted with sector professionals such as designers, architects, engineers, and contractors.[10,13-19] For example, Nassar *et al.*'s study[13] addressed the issue in its purely technical dimension and developed software that included 16 different performance criteria for material selection. In the study of Treloar *et al.*,[14] material selection was examined in terms of both embodied energy and operational energy requirements. Alibaba and Özdeniz developed a selection system for architects based on the performance requirements of building elements.[15] Wang *et al.*[16] used the life cycle analysis methodology to evaluate design alternatives and evaluated life cycle environmental impacts in terms of extended cumulative exergy consumption. Al Jaber *et al.*[17] emphasized that the perception that virgin materials are cheaper in the short term affects material selection decisions, which leads to the constant depletion of natural resources. Gonzalez and Navarro[19] found that by carefully selecting materials with low environmental impact, CO_2 emissions during the construction phase could be reduced by up to 30%. In contrast to previous research in the field, this study attempted to uncover the viewpoints of consumers about sustainability and material choices. The expectations of the public, who are mostly buyers of completed houses, regarding building materials – particularly finishing materials – could therefore be made clear. This will assist the designers and contractors in choosing materials in a more logical manner. Moreover, citizens directly decide themselves on the building materials they will use when building their own houses, buying incomplete houses, and completing them themselves, or making large-scale renovations in their homes.

In this regard, the current study provides data for material manufacturers and sellers. The views of citizens on the relationship between building materials and sustainability constitute another important piece of result in the study. The study's findings will thereby guide sustainability initiatives. For this purpose, the importance of 11 material selection criteria and seven material sustainability criteria, which were determined based on the literature, were investigated through a questionnaire study. The most important material selection criterion in the study was found to be durability, as it provides very beneficial for reducing costs associated with demolition, early repair, or maintenance, and minimizing maintenance, waste, and environmental pollution, thereby contributing to sustainability. The participants identified material availability as the second most important factor, probably because it is important for ensuring the schedule-compliant progression of the work and avoiding additional costs. The participants in the study attributed relatively high importance to sustainability. The study revealed that a durable and esthetic finishing material is more valuable to users than a trendy material. The study revealed that, contrary to popular belief, the participants can bear significant additional costs for sustainable materials. With the revelation of non-professionals' perspectives on material selection and sustainability, this study provides novel and important insights into the existing literature.

2. Materials and methods

This study was conducted in accordance with the method presented in Figure 1, by determining the material selection and sustainability criteria through a literature review, conducting the survey, performing appropriate analyses, determining the importance of the criteria, and discussing the results.

A survey consisting of two main sections was applied within the scope of the study. In the first section, participants were asked to rate their perspectives toward the importance of 11 different material selection criteria, which were determined based on the literature and presented in Table 1, assuming that they were building their own houses. Participants made their preferences according to a 5-point Likert scale ranging from unimportant to absolutely very

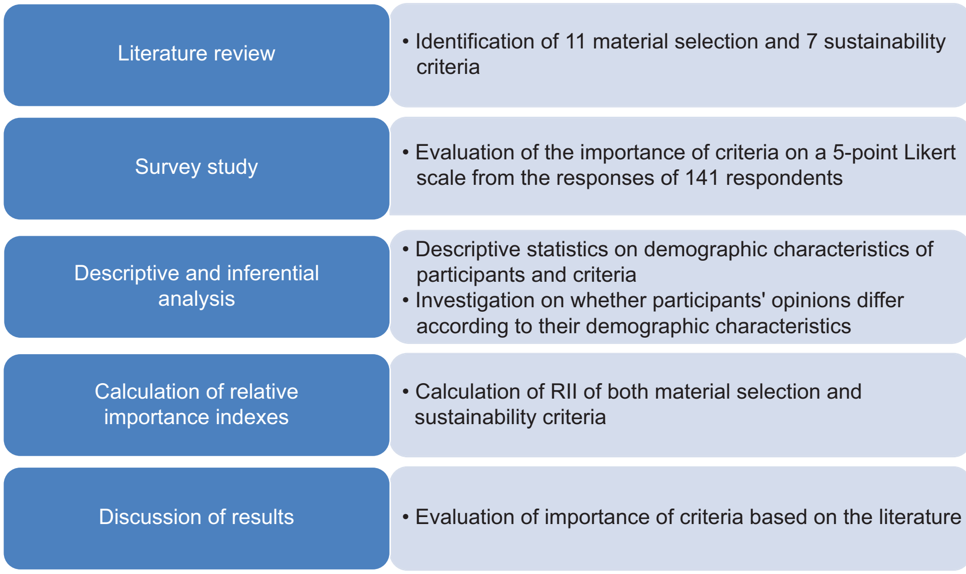

Figure 1. Methodology used in this study
Abbreviation: RII: Relative importance index.

Table 1. Material selection criteria

No.	Criteria	References
1	Durability of the material	Designing Buildings, 2021; Cabral and Blanchet, 2023[22,23]
2	Availability of material	Patel and Vyas, 2011; Pitkänen 2024[24,25]
3	Availability of skilled labor force	Gudienė *et al.* 2013; Alawag *et al.* 2023. Akomah *et al.* 2020[26-28]
4	Sustainability	Mathiyazhagan *et al.*, 2019; Chen *et al.*, 2021[29,30]
5	Esthetics of the material	Aydin *et al.*, 2019; Rockfon, 2022; Besten, 2020[31-33]
6	Ease of maintenance	Mohanta, and Das, 2023; Zhu *et al.*, 2018[34,35]
7	Ease of construction	Haq *et al.*, 2022[36]
8	Construction speed	Celentano *et al.*, 2019[37]
9	Initial cost of material	Dinh *et al.*, 2024[38]
10	Maintenance cost	Sahlol *et al.*, 2021; Yıldız *et al.*, 2024[12,39]
11	Popularity of the material	Jaffar *et al.*, 2024[40]

Table 2. Sustainability criteria related to material selection

No.	Criteria	References
1	Being durable and easy to maintain	Carp, 2020; Yang, 2023[41,42]
2	Being energy efficient	Takano *et al.*, 2014 Hong *et al.*, 2015[43,44]
3	Being cost-effective	Arch 20, 2024[45]
4	Being non-toxic	Abera, 2024[46]
5	Being renewable	Lin (2021) [47]
6	Being recyclable or being produced of recyclable materials	Cudjoe *et al.*, 2021[48]
7	Being local	Champ, 2024; Ibuchim *et al.* 2010[49,50]

important. In the second section, participants were asked to indicate the importance of the seven criteria regarding the sustainability of the materials presented in Table 2, again on a 5-point Likert scale. In addition, respondents were asked how much additional cost they would bear for adopting more sustainable materials.

The survey was conducted with 141 respondents and the results were analyzed using the Statistical Package for Social Sciences (SPSS) 26.0[51] program. Since the study aimed to determine the general views of citizens on material selection and sustainability criteria, convenience sampling, instead of purposive sampling, was used. Convenience sampling involves the inclusion of individuals in the study because they are willing, available, or easy to reach or communicate with on a practical level. First, reliability analysis is required to determine whether the scale is reliable or not. Then, inferential analyses are needed to see whether the results can be generalized and interpreted collectively. It is possible to conduct inferential analyses with parametric or non-parametric tests. To decide which tests to use, normality tests were performed and accordingly, hypotheses were tested with appropriate methods. It is possible to generalize the tested hypotheses as follows:

> *H_o: There is a significant difference between the opinions of the participants in terms of material selection/sustainability criteria according to gender/age group/education level/work experience/profession.*

The statistical analyses used in the study were descriptive analysis, reliability analysis, independent sample *t*-test, analysis of variance (ANOVA), Mann–Whitney *U* test, and Kruskal–Wallis test.

3. Findings

According to the results of the survey, participants' demographic data, reliability of the scales, and whether the opinions of the participants differed according to their demographic data were examined. The relative importance of material selection criteria and material sustainability criteria were determined.

3.1. Demographic findings

A data set can be quantified and summarized using descriptive analysis by counting or ranking values in a quantitative or graphical format, or using quantitative numerical values.[52] Descriptive statistics were used to illustrate the participants' demographics. Figure 2 provides the participants' demographic information. Accordingly, 52.5% of the participants were male. Over half of the participants were younger than 30, and most of them were university students or graduates. Almost half of the participants have 0 – 5 years of work experience. In terms of occupation, 34% of the participants are students, whereas the rest are architects, engineers, health professionals, civil servants, and tradesmen.

3.2. Descriptive statistics and reliability analysis results of the scales

Reliability analysis is the process of evaluating the consistency of a scale or measurement instrument. The objective is to determine whether a scale produces consistent results under consistent conditions following multiple administrations. Cronbach's alpha is the most often used measure of internal consistency (or "reliability"). It is most used in surveys and questionnaires with multiple Likert questions that add up to a scale. Cronbach's alpha is calculated by comparing the scores of each scale item to the total score for each observation.[53] Table 3 displays the reliability coefficients and descriptive data for the scales used in the study. The reliability values of the scales were determined to be 0.71 and 0.77. These values were above the cutoff values of 0.5 suggested by Cronbach and Helmstater and 0.7 suggested by Bowling and Shah, which indicates a reliable scale.[54-56]

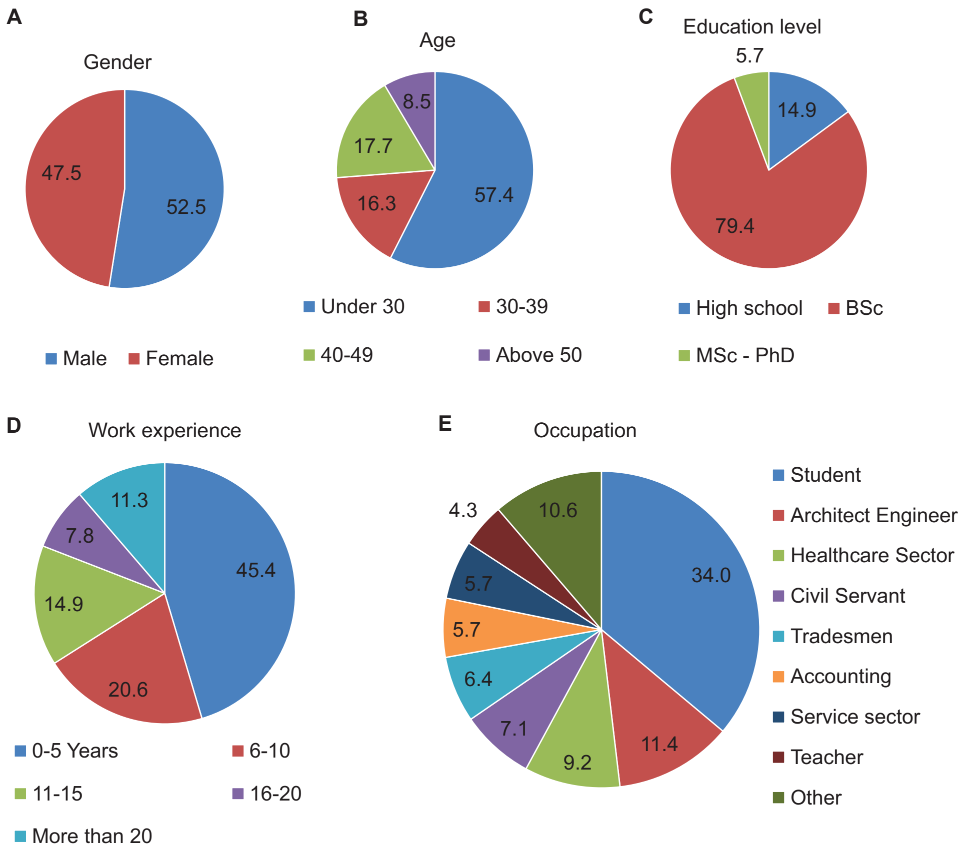

Figure 2. (A-E) Distribution of participants according to demographic characteristics

3.3. Relationships between demographic variables and material selection criteria

The main purpose of the study is to determine the importance levels of material selection criteria and sustainability criteria. For this, it is first necessary to reveal whether the participants' opinions differ according to their demographic characteristics. A normality test was carried out since the tests to be used were chosen based on whether the data were normally distributed.

3.3.1. Normality test

Several techniques can be used to determine whether the data are normally distributed. Using one of these methods, we determined the statistics value or standard error value for skewness and kurtosis of the data, as presented in Table 4. Skewness is a metric for symmetry. If a data set or distribution appears the same on the left and right of the center point, it is said to be symmetric. Kurtosis quantifies how heavy-tailed or light-tailed the data are in comparison to a normal distribution.[57] Mayers[58] states that a threshold value of ±3.29 should be used for samples larger than 100. Accordingly, the material selection criteria data have a normal distribution (0.54; −2.20), whereas the sustainability criteria data have a non-normal distribution (4.13; 2.12).

Another method is to conduct the Shapiro–Wilk test for small samples and the Kolmogorov–Smirnov test for large samples. Kolmogorov–Smirnov is used to test whether the distribution of random numbers generated by any method conforms to a uniform distribution within the desired confidence intervals.[59] Since the number of data was 141, the Kolmogorov–Smirnov test results were taken as basis. In the Kolmogorov–Smirnov test, a $P > 0.05$ indicates normal distribution, while a $P < 0.05$ indicates non-normal distribution.[60] The results of the Kolmogorov–Smirnov test are displayed in Table 5. This indicates that the sustainability criteria data exhibits a non-normal distribution, whereas the material selection criteria data exhibits a normal distribution. According to these results, it would be appropriate to proceed with parametric tests for the normally distributed material selection criteria data and nonparametric tests for the non-normally distributed sustainability criteria data.

Table 3. Descriptive statistics and the scales' reliability values

Variable	*n*	Number of items	Mean	Min.	Max.	Cronbach's alpha
Material selection criteria	141	11	3.970	3.142	4.716	0.71
Sustainability criteria	141	7	3.842	3.035	4.504	0.77

Table 4. Scales' kurtosis and skewness values

	Statistic	Standard error	Statistic/Standard error
Material mean			
Mean	3.9703	0.04456	
Skewness	0.110	0.204	0.54
Kurtosis	−0.896	0.406	−2.20
Sustain mean			
Mean	3.8419	0.06353	
Skewness	−0.844	0.204	4.13
Kurtosis	0.859	0.406	2.12

3.3.2. Inferential analysis results

The goal of inferential statistics is to derive analytical expressions for hypothesis testing or prediction on the nature of the statistical main mass.[61] Tests that compare the means of two or more groups to ascertain whether the difference is random or statistically significant are known as inferential analysis tests. To see whether the opinions differed according to demographic characteristics, the *t*-test and ANOVA were used for the material selection criteria, whereas the Kruskal–Wallis and Mann–Whitney *U* tests were utilized for the sustainability criteria.

3.3.3. Test results according to gender of participants

In this section, the analysis focuses on investigating whether there is a significant difference in perspectives among participants according to their gender. Figure 3 shows the means of material selection criteria and sustainability criteria according to gender. Very slight variations exist between the means of both groups in terms of both material selection criteria and sustainability criteria (3.9558 – 3.9864 and 3.8668 – 3.8145, respectively).

For the material selection criteria, an independent sample *t*-test, which is one of the parametric tests, was performed. The independent sample *t*-test analyzes the means of two independent groups to ascertain whether there is statistical evidence that the means of the groups are significantly different. In this test, if the *P*-value found in Levene's test exceeds 0.05, there is no difference between the groups. In this case, the values in the first row are taken into consideration. Accordingly, the *P*-value is 0.733, and there is no significant difference between genders (Table 6). Sustainability criteria were analyzed with the non-parametric Mann–Whitney *U* test. This test compares two sample means and tests whether

Table 5. Kolmogorov–Smirnov test results of the scales

	Statistic	df	Sig.
Material mean	0.060	141	0.200
Sustain mean	0.111	141	0.000

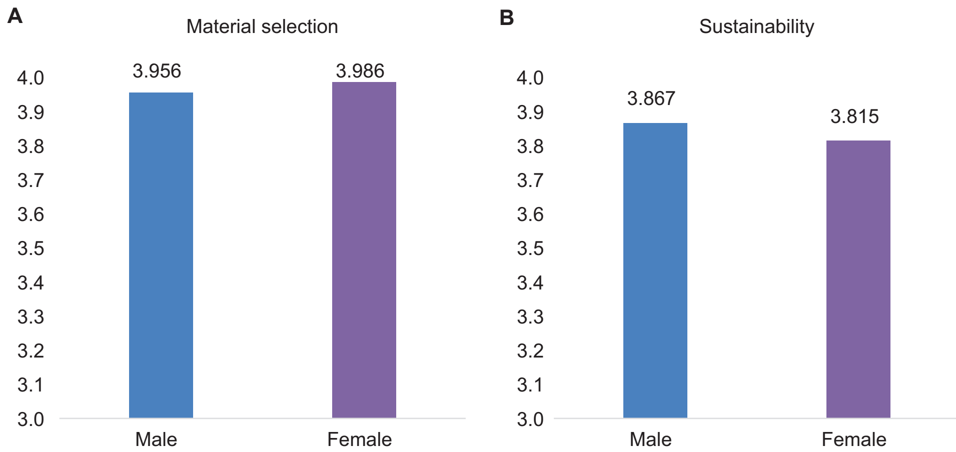

Figure 3. (A and B) The means of material selection criteria and sustainability criteria according to gender

the two sample means are equal. According to Table 7, the *P*-value was 0.851, indicating that there is no significant difference between genders.

3.3.4. Test results according to age groups

In the analysis of the participants according to age groups, ANOVA for material selection criteria and Kruskal–Wallis tests for sustainability criteria were performed. If the number of samples or groups ≥3, whether there is a difference between the means of the groups is determined with ANOVA for parametric data and the Kruskal–Wallis test for non-parametric data. Since the $P > 0.05$ (0.877 – 0.416), it was concluded that there was no significant difference between the groups (Tables 8 and 9).

The means of material selection and sustainability criteria which the participants attach importance to, according to their age groups, are presented in Table 10. Although there was no statistically significant difference, especially the sustainability mean was higher for the group over 50 years of age.

3.3.5. Test results according to participants' education level

Parametric ANOVA and non-parametric Kruskal–Wallis test were used to examine whether the participants' opinions differed according to their level of education. The *P*-value for material selection criteria was found to be 0.887 (Table 11) and 0.923 (Table 12) for sustainability criteria. Accordingly, there is no significant difference according to education level.

The material selection and sustainability means of the participants according to their education level are presented in Table 13. Differences between the means of the groups according to the level of education of the participants are very small.

Table 6. Results of the *t*-test according to gender

	F	Sig.	t	df	Sig. (2-tailed)
Material mean					
Equal variance assumed	0.206	0.650	−0.342	139	0.733
Equal variance not assumed			−0.343	138.359	0.732

Table 7. Mann–Whitney *U* test results according to gender

	Mann–Whitney U	Wilcoxon W	Z	Asymp. sig. (2-tailed)
Sustain mean	2433.500	5208.500	−0.188	0.851

Table 8. Results of ANOVA according to age groups

	Sum of squares	df	Mean square	F	Sig.
Material mean					
Between groups	0.195	3	0.065	0.228	0.877
Within groups	39.004	137	0.285		
Total	39.198	140			

Table 9. Kruskal–Wallis test results according to age groups

	Kruskal–Wallis H	df	Asymp. sig.
Sustain mean	2.847	3	0.416

3.3.6. Test results according to participants' work experience

The *P*-value for the material selection criteria in the ANOVA was 0.604 (Table 14), whereas the Kruskal–Wallis test's *P*-value for the sustainability criteria was 0.241 (Table 15), according to the participants' work experience. Accordingly, there is no significant

Table 10. Descriptive statistics according to participants' ages

Age	Material mean	Sustain mean
Under 30		
Mean	3.9787	3.8166
n	81	81
30 – 39		
Mean	3.9091	3.8261
n	23	23
40 – 49		
Mean	3.9564	3.7943
n	25	25
Over 50		
Mean	4.0606	4.1429
n	12	12
Total		
Mean	3.9703	3.8419
n	141	141

Table 11. ANOVA results according to participants' education level

	Sum of squares	df	Mean square	F	Sig.
Material mean					
Between groups	0.068	2	0.034	0.121	0.887
Within groups	39.130	138	0.284		
Total	39.198	140			

Table 12. Kruskal–Wallis test results according to participants' education level

	Kruskal–Wallis H	df	Asymp. sig.
Sustain mean	0.160	2	0.923

Table 13. Descriptive statistics according to participants' education level

Education level	Material mean	Sustain mean
High school		
Mean	3.9221	3.7279
n	21	21
BSc		
Mean	3.9813	3.8763
n	112	112
MSc-PhD		
Mean	3.9432	3.6607
n	8	8
Total		
Mean	3.9703	3.8419
n	141	141

Table 14. ANOVA results according to participants' work experience

	Sum of squares	df	Mean square	F	Sig.
Material mean					
Between groups	0.770	4	0.192	0.685	0.604
Within groups	37.643	134	0.281		
Total	38.413	138			

Table 15. Kruskal–Wallis test results according to participants' work experience

	Kruskal–Wallis H	df	Asymp. sig.
Sustain mean	5.480	4	0.241

difference between the groups in terms of their work experience.

Table 16 displays the means of material selection criteria and sustainability criteria based on participants' work experience. Although statistical tests show that the differences are not significant, participants with more than 20 years of work experience had the highest means for both material selection and sustainability criteria.

3.3.7. Test results according to participants' occupations

Participants' occupations were divided into nine categories based on their responses to the questionnaire. ANOVA and Kruskal–Wallis tests were used to determine whether the perspective disparity among these nine occupational groups were significant. Since the test results show that the $P > 0.05$ (0.197 – 0.057) (Tables 17 and 18), it is concluded that there is no significant difference between the groups.

In the analysis of material selection criteria, civil servants recorded the highest mean (4.2841) whereas health-care professionals had the lowest mean (3.7692). Results turned out to be the same for sustainability criteria analysis, with civil servants again recording the highest mean (4.3125) and health-care professionals the lowest (3.5846). For architects/engineers, their means were close to the general mean (4.0101, 4.0079).

3.4. Criteria considered in the selection of building materials

The results of the inferential analysis show that there is no significant difference between the participants' perspectives regarding both material selection and sustainability criteria according to any demographic characteristics. In this case, it is possible to generalize by determining the relative importance coefficients of the criteria. The following formula was used to calculate the relative importance index of the criteria:

$$IRI = \Sigma W / A * N \quad \text{(I)}$$

Where:

- *IRI*: Index of relative importance;
- *W*: The weights given by each participant for that proposition (1 – Not important, 2 – Somewhat important, 3 – Average important, 4 – Very important, and 5 – Absolutely very important;
- *A*: The highest weight value (it is five in this case);
- *N*: Total number of participants (it is 141 in this case).

Table 16. Descriptive statistics according to participant's work experience

Work experience (years)	Material mean	Sustain mean
0 – 5		
Mean	3.9361	3.7612
n	64	64
6 – 10		
Mean	3.9122	3.7882
n	29	29
11 – 15		
Mean	4.0606	3.7891
n	21	21
16 – 20		
Mean	3.8283	4.0159
n	9	9
More than 20		
Mean	4.0966	4.1071
n	16	16
Total		
Mean	3.9614	3.8273
n	139	139

Table 17. ANOVA results according to participants' occupations

	Sum of squares	df	Mean square	F	Sig.
Material mean					
Between groups	3.090	8	0.386	1.412	0.197
Within groups	36.108	132	0.274		
Total	39.198	140			

Table 18. Kruskal–Wallis test results according to participants' occupations

	Kruskal–Wallis H	df	Asymp. sig.
Sustain mean	15.086	8	0.057

The relative importance index of the criteria for material selection is presented in Table 19. Accordingly, the most important criterion was the durability of the material, followed by the availability of the material and the availability of qualified labor. The popularity of the material was regarded as the least important criterion.

The relative importance index of the sustainability criteria is presented in Table 20. The durability and maintainability of the material is the most important criterion in terms of sustainability. Energy efficiency and cost-effectiveness were the next most important criteria while being local was considered relatively the least important criterion.

About 30% of the respondents claimed that they would bear an additional cost ranging from 5% to 10% for adopting sustainable materials (Figure 4). Twelve percent of respondents said they would not pay more in this respect.

Table 19. Relative importance indexes of the criteria for material selection

Rank	Criterion	Mean	IRI
1	Durability of the material	4.7163	0.943
2	Availability of material	4.1773	0.835
3	Availability of skilled labor force	4.1631	0.833
4	Sustainability	4.0142	0.803
5	Esthetics of the material	3.9929	0.799
6	Ease of maintenance	3.9787	0.796
7	Ease of construction	3.8865	0.777
8	Construction speed	3.8723	0.774
9	Initial cost of material	3.8652	0.773
10	Maintenance cost	3.8652	0.773
11	Popularity of the material	3.1418	0.628

Table 20. Relative importance indexes of sustainability criteria

Rank	Criterion	Mean	IRI
1	Being durable and easy to maintain	4.5035	0.901
2	Being energy efficient	4.0851	0.817
3	Being cost-effective	4.0851	0.817
4	Being non-toxic	4.0426	0.809
5	Being renewable	3.8369	0.767
6	Being recyclable or being produced of recycled materials	3.3050	0.661
7	Being local	3.0355	0.607

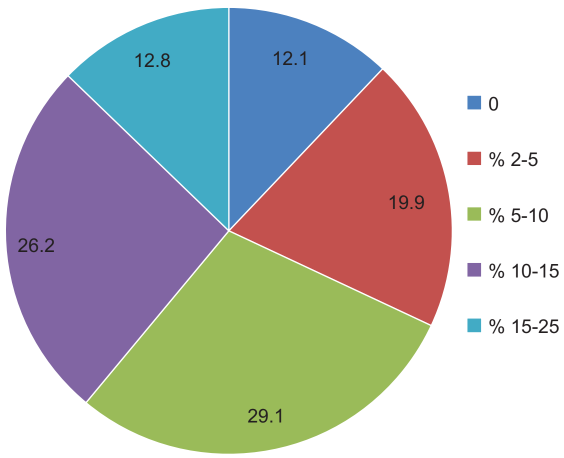

Figure 4. Distribution of participants according to additional costs they would bear for adopting sustainable materials

4. Discussion

The present study examined the respondents' perspectives toward the relative importance of 11 material selection criteria and seven sustainability criteria. In the study of Nassar *et al.*,[13] beyond various technical features, durability, ease of maintenance, and initial cost were determined as selection criteria for different building materials. Alibaba and Özdeniz[15] proposed different selection criteria for different building elements. In addition to many technical criteria, durability, appearance, cost, and construction speed were considered material selection criteria. Besides technical properties such as physical, mechanical, and thermal properties, a literature review conducted by Ramalhete *et al.*[18] examining digital tools for material selection identified cost and esthetics were material selection criteria. As in many other studies in the literature, none of these studies have determined the level of importance of the criteria. The studies have generally suggested determining the weights of the material selection criteria by the designers.

Inferential analyses conducted in this study showed that the participants' opinions did not differ according to demographic characteristics in terms of material selection or sustainability criteria. In other words, gender, age, education level, profession, and work experience do not affect the participants' preferences, and thus, it is feasible to generalize the results.

Durability was found as the most important material selection criterion. Durability refers to the resistance of a material to deterioration over time. A building is typically exposed to daily wear and tear caused by users; weather conditions such as rain, frost, sun, and heat; environmental conditions such as humidity, soil, and groundwater impact; and atmospheric pollution, and these factors cause significant deterioration and thus a decrease in durability.[22] In addition to the reduction in durability, these factors generally change the appearance of the fabrications for the worse, except in some special cases, such as copper oxidizing to form green coloration over time. Durable materials provide crucial beneficial effects in terms of reducing costs associated with demolition, early repair, or maintenance; and minimizing maintenance, waste, and environmental pollution, thereby contributing to sustainability.[42] Since such concepts about material durability have been deeply ingrained in participants' mindsets, they rated it as a very important criterion.

The main objective of materials management at the construction site is to ensure that construction materials are available at the point of use when needed. This is crucial for ensuring project progression in adherence to the proposed timeline and preventing extra expenses.[24,25] In this study, the participants identified the availability of materials as the second most critical factor in view of the aforementioned requirements. One of the problems faced by the construction industry in recent years is the gradual decrease in the qualified labor force. However, the success of a construction project depends primarily on qualified labor as one of the critical factors of production.[26-28] An unqualified worker may do an unsatisfactory job in installing a beautiful and high-quality ceramic tile, or an inept supervisor may fix an expensive wallpaper in an unsightly manner. It is found that the participants attach great importance to the qualified labor force based on their work experiences.

Surprisingly, we found that the respondents attached high importance to sustainability, an indication that participants are becoming more conscious of environmental issues and the advantages of sustainable materials, including affording better performance at lower costs, a more comfortable and healthier living environment, and increased life satisfaction.[29,30]

Beautiful architecture appeals to our emotions and makes us feel better. Therefore, appearance is an important factor determining the overall satisfaction of customers and is recognized as the main driving force behind marketability.[31-33] The respondent's prioritization of esthetics right after the criteria that are beyond their control, such as durability, qualified labor, and material availability, is also an important finding of the study.

Another important finding of this study is that respondents regard ease and speed of manufacture, initial cost, and ease and cost of maintenance as relatively less important. This result suggests that participants are willing to pay more for durable and well-crafted products, wait longer for completion, and would like to care less about maintenance. It is crucial that designers who choose materials prioritize durability, availability, availability of skilled labor, and esthetics and that marketing is done with this in mind.

Another result of the study is that the material's popularity is the least important criterion for the participants. This shows that the participants do not consider building materials as goods and anticipate prolonged usage of these materials. For users, a durable and esthetic finishing material is more valuable than a trendy material.

The sustainability criteria in the selection of materials covered in this study have been largely suggested also by Treloar *et al.*[14] In their study, long-lasting materials that do not require frequent replacement, local materials instead of those transported over long distances, materials incorporating high content recycled or previously used matters, materials with low embodied energy, and materials that reduce net energy usage during the operation period are found as the preferred choices. In Lin's study investigating the role of sustainable building materials in ecological construction,[47] durability, low maintenance requirements, energy saving, non-toxicity, and local origin were the sustainability criteria emphasized.

Interestingly, the French word for sustainability is durabilité.[41] The durability of construction materials is at the heart of the sustainability of the built environment. A material's overall environmental impact will decrease if it does not require frequent replacement. On the other hand, flimsy materials lead to premature deterioration, safety risks, economic burdens, and negative environmental impacts, negatively impacting sustainability in environmental, economic, and social dimensions.[42] The ease of maintenance of sustainable materials means that they do not require frequent cleaning or painting, thus saving time and resources in ways similar to the durability context. The respondents' awareness of this whole situation has led them to attribute the highest importance to the durability and ease of maintenance of the material. On the other hand, the poor quality of building materials may be an obstacle to implementing the circular economy in the construction sector.[17]

The second most important aspects in terms of sustainability were energy efficiency and cost-effectiveness, to which the same degree of importance was attributed. Energy efficiency is one of the first aspects regarding sustainability for buildings that need to be dealt with. Significant savings can be achieved using good thermal insulation and efficient heating and cooling equipment.[43] Taking measures to improve the energy efficiency of buildings can potentially save 20 – 40% of energy in the construction sector.[44,62] On the other hand, studies reported that the share of embodied energy in life cycle energy use can be as high as 46% in low-energy buildings and 38% in conventional buildings.[63] Using cost-effective materials can reduce strain on the budget and allow for a sustainable construction approach. Materials such as recycled steel, rammed earth, adobe, bamboo, and cork can offer the same strength and beauty as traditional materials but are more environmentally friendly and cost-effective. By prioritizing cost-effective materials, architects and designers can create beautiful, functional spaces that are both affordable and sustainable.[45]

Participants attributed relatively high importance to non-toxic and renewable materials. In contrast, the two criteria they attach lower importance to were the use of recyclable or recycled materials and materials extracted or produced locally. Research indicated that there is a prevalent negative viewpoint toward reclaimed materials, with a preference for buildings constructed using new materials rather than those utilizing recovered materials.[17] However, using recycled materials and using local materials are important factors for sustainability. The circular economy approach to building materials involves a continuous flow of materials through procurement, use, dismantling, reuse, recycling, and recovery.[17] Similarly, Ibuchim *et al.*[50] pointed out the importance of using recycled and local materials in green buildings. Embedded emissions of materials can account for up to 68% of 50-year life cycle emissions.[64] More than 30% of greenhouse gases are estimated to be emitted from the construction sector in developing countries.[65] Using recyclable or recycled materials can significantly contribute to sustainability by reducing resource consumption, minimizing environmental damage, and reducing waste.[48] A sustainable building is considered a long-term strategy to reduce life cycle costs and passive environmental impacts.[38]

Using locally sourced building materials makes it possible to create beautiful, durable structures while contributing to reducing carbon emissions, combating climate change, and minimizing the environmental footprint.[49,50] Local materials, such as bamboo, stone, adobe, cork, laminated timber, plant-based polyurethane rigid foam, sheep's wool, and straw bales, can be generally natural and inexpensive materials with low environmental impact. Those materials can be obtained from the regions close to the construction site, as well as materials obtained from factories in the immediate vicinity. Local materials contribute to environmental sustainability and economic sustainability owing to their low costs, as well as social sustainability through their reflection of the region and its culture.

One of the obstacles to sustainable building construction is its cost.[66] Sustainable materials are generally known to increase initial construction costs but reduce costs over the building lifecycle.[12] Participants indicated how much additional cost they would bear for more sustainable materials. The percentage of respondents who said they would not bear any extra cost was approximately equal to of respondents who said they would bear an extra cost measuring between 15% and 25%. On the other hand, more than half of the participants stated that they could bear an extra cost between 5% and 15%. This finding indicates that cost being an obstacle to sustainable buildings does not hold true; on the contrary, the usage of sustainable materials can be integrated as part of the marketing strategy, even if the incurred cost is raised.

5. Limitations and future directions

This study was carried out in a single city, by surveying respondents in a limited sample. Five different demographic characteristics – gender, age, occupation, education level, and work experience – were the basis for inferential analysis. New studies can be conducted with more participants from different cities and neighborhoods and with varying income levels. In addition, it is possible to conduct studies based on multicriteria decision analysis methods in the future to determine the importance weights of the criteria.

6. Conclusion

In addition to being safe, cost-effective, esthetically pleasing, durable, and functional, a building must also be sustainable, a trait that has been gaining traction and importance nowadays. To fulfill all these expectations, besides applying correct design and workmanship, adopting appropriately chosen materials is extremely important.

Despite the extensive investigations on material selection, these studies generally address the subject technically, mainly from the perspective of technical personnel such as architects and engineers. However, understanding the perspectives of citizens, who are often the customers of finished buildings and sometimes of building materials, is also critical. This allows for better meeting customers' needs and for executing proper marketing strategies.

Contrary to popular belief, this study revealed that durability, material availability, and skilled labor availability are important criteria, instead of popularity and initial cost of the material. Again, it is important to restate that sustainability is highly regarded by most people, evident by a significant portion of people who are willing to bear additional costs for sustainability. Accordingly, designers and contractors should make more efforts in the aspect of sustainability and make this theme central to their marketing strategies.

The revelation of the primary expectations of citizens of building materials and their perspectives on sustainability criteria offer refreshing insights that have huge implications for future research and works. Different stakeholders of the construction sector, such as designers, contractors, and material producers, can leverage the findings of this study in their designs, construction, and marketing strategies.

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Conflict of interest

The author declares no conflict of interest.

Author contributions

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The article complies with national and international research and publication ethics. Ethics Committee approval was obtained with the decision numbered 04/17 taken at the meeting of Ankara University Ethics Committee dated 05/07/2024.

Consent for publication

Human subjects participating in the survey were informed that any data related to their personal information would not be included in the study and that the results would be analyzed anonymously. Their verbal consent was obtained.

Availability of data

Data are available from the corresponding author upon reasonable request.

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Evaluating the usage of a building code calculator app as a design tool

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Abstract

Building code knowledge is essential for designers, but it can be challenging to learn and master. While automated code compliance tools assist in navigating these complexities, they are typically used later in the design process. This study introduces the Building Code Calculator App as an early-stage design tool. Grounded in cognitive load theory, the app simplifies information to simplify the learning process. It also incorporates concept mapping, a visual tool that aids in knowledge construction. This research aimed to examine the effectiveness of the Building Code Calculator App as a tool for design education. The app offers a visual guide to building codes and includes calculation features with explanations. It was hypothesized that the app would improve designers' knowledge and skills while reducing their stress levels as they work on building code tasks. The study also predicts that the app will be adopted by designers in the future. A survey was conducted with senior interior design students after they completed a building code task using traditional methods and then used the app. All of the survey participants indicated the usefulness of the Building Code Calculator App in assisting the application of building code's content and expressed disposition to use the app in the future. Results also confirmed that using the app lowered the participants' stress levels, demonstrating its value as a design tool. In conclusion, these results advocate for a more comprehensive approach to building code education that leverages technology to provide practical, hands-on learning opportunities.

Keywords: Building code; Interior design; Cognitive load; Mobile app; Design tool; Digital tool

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1. Introduction

The significance of building codes and standards in the field of building design is crucial. Certified designers must be able to accurately interpret and apply national models, state-specific codes and standards, as well as federal and state laws, including the Americans with Disabilities Act. This knowledge is essential in creating safe, sustainable, affordable, accessible, and resilient buildings, such as convention centers, hotels, and airport terminals, where large groups of people gather. As key protectors of public health, safety, and welfare in the built environment, designers possess expertise critical to ensuring public safety and are obliged to adhere to codes and standards in their profession.[1,2]

The Federal Emergency Management Agency conducted a nationwide study, *Building Codes Save*, which reveals that adopting and enforcing both the International Building Code® and the International Residential Code® could reduce property losses by US$132 billion. According to the study, as of November 2020, over half (65%) of the U.S. counties, cities, and towns had not adopted updated building codes. In some countries, the rate of code adoption is even lower, increasing the risk of hazardous environments.[3] While building codes are often seen as restrictive, they ultimately serve to enhance the quality and safety of built environments, fostering innovation within the framework of established guidelines.

These codes govern various aspects of design, including structural integrity, fire safety, accessibility, and environmental efficiency. Code analysis is a step-by-step process that begins with determining occupancy levels, which influences almost every other decision. Familiarity with building codes is crucial for building designers, yet many face challenges due to the complexity and frequent updates of these regulations.[4] Design tools, such as automated code compliance checking, can aid designers in navigating these complexities and enhance their understanding of relevant codes. However, those tools are mostly helpful toward the end of the design process. The Building Code Calculator App introduced in this study was evaluated as an early-stage design tool.

This study employed a survey design with a mixed-method approach to assess whether the Building Code Calculator App facilitated cognitive progression through Bloom's Taxonomy and reduced stress during building code calculation tasks. Nineteen senior interior design students from a CIDA-accredited program participated voluntarily in this IRB-approved study after giving informed consent. Participants completed building code scenarios using traditional methods and the app, which was designed to reduce cognitive load and minimize calculation errors. Afterward, they responded to a questionnaire assessing perceptions of building codes, cognitive skills, technology adoption, and stress levels. Data, collected through Qualtrics, included demographic information for additional analysis. The process took approximately 40 min per participant.

2. Literature review

2.1. Automated building code compliance checking

The process of checking building designs for compliance with regulations is time-consuming and prone to errors. The automation of this process has been explored since the 1960s, gaining momentum with the rise of Building Information Modeling (BIM). The use of the Industry Foundation Classes format under the BIM platform has improved collaboration and information exchange, aiding the development of automated checking systems. These systems generally consist of stages such as rule interpretation, building model preparation, rule execution, and reporting, with rule interpretation being the most crucial and complex. Various techniques have been explored to improve the accuracy of rule interpretation, including utilizing software like Solibri Model Checker; developing a plug-in application; and establishing object-based, logical, and ontological approaches.[5]

2.2. Building code in design education

Traditional methods of teaching building code topics are often perceived as passively learned content with little appeal that minimizes student engagement and immersion. To address this, a study was conducted to discuss the development and effectiveness of self-contained teaching modules that can be incorporated within existing courses. These modules utilize active content with engaging topics that demonstrate the relevance of building codes to students' careers.[6] A more recent study's findings indicate that the current approach to teaching building codes is ineffective and requires revision. While the researchers acknowledge teaching building code as a separate course is a positive step in bridging the gap between professional practice and university education, it is also important to incorporate building code into theoretical and practical courses. To achieve this, course content should be revised to include a stronger focus on relevant topics related to building code.[7] Another interior design-focused study revealed that the topic of laws, codes, and standards ranked first or second in importance among various content units. These findings suggest that interior design curricula should place greater emphasis on laws and codes to better prepare entry-level designers for success in the marketplace.[8]

2.3. Multimedia learning

One of the benefits of computer technology for educational purposes is its capacity to combine text, sound, images, animations, and video to create multimedia learning environments.[9,10] This learning method has become widely used and can result in more effective, efficient, and enjoyable learning experiences[10] based on how they are used along with students' learning preferences.[9] Researchers have been challenged with finding the most effective media for learning. Mayer's cognitive theory of multimedia learning suggests that multimedia learning is composed of three levels of cognitive processing, namely selecting relevant information, organizing information into visual and verbal models, and integrating models with prior knowledge.[9] This new information is stored as mental representations called schemata in the long-term memory – a process required for meaningful learning.[10] Multimedia learning improves comprehension, lowers anxiety, and improves motivation.[11] Displaying information both visually and verbally helps learners build integrated mental models that make it easier for them to remember information. However, adding repeated and irrelevant visual or verbal information affects learning and increases extraneous load.[9]

Mayer developed five principles that lowered extraneous processing in multimedia learning environments. These principles include coherence, signaling, redundancy, spatial contiguity, and temporal contiguity. The coherence principle suggests that removing unnecessary material can liberate memory capacity to build schemata. The signaling principle suggests that learning can be more effective when cues are added to emphasize the major key point of the material, which can be done through verbal or visual signaling. Meanwhile, the redundancy principle indicates that multimedia presentations are more effective when using graphics and narrations instead of combining on-screen text, graphics, and narrations. This is due to the text causing visual overload.[12] Therefore, replacing visual text with verbal text and adding visual cues to the instructions can reduce mental efforts.[13] Moreover, the spatial contiguity principle suggests that learning is enhanced when related text and pictures are presented and placed closely together instead of separately. This organization can help the learner maintain both types of information longer in their working memory, improving their active learning. Finally, the temporal contiguity principle refers to words and pictures or narrations and animations that correspond to each other and should be presented together instead of one after the other.[12]

2.4. Cognitive load

Cognitive load theory, developed by Sweller in 1991,[14] is a model that explains how the mind processes multimedia information. The brain has limited working memory to process visual and verbal information. Learning new skills and tasks affects the working memory.[15] There are three types of cognitive load, intrinsic load, extraneous load, and germane load. Intrinsic load is the difficulty of the material or task being learned, the harder the task the more the intrinsic load. Extraneous load is the mental effort imposed based on the design and presentation of the learning material.[9] Therefore, the better the learning content is presented the lower the extraneous load.[10] While germane load is the mental effort used to understand new information and incorporate it into existing knowledge or schemata.[9] The process of creating schemata helps with students' learning.[10]

Cognitive load can determine the effectiveness of the learning or teaching method. Typically, lower cognitive loads are linked to higher learning performances, whereas poorer performances are linked to higher loads.[11] Recent studies have shown that intrinsic load can be adjusted to decrease load. Therefore, learning material should be designed to minimize extraneous load, allowing mental effort to focus on germane load. Humans have two channels; one is used to process visual information, and the other is used to process auditory information. An approach has been suggested to display part of the learning content visually and the other part verbally.[9]

Homer *et al.*[9] conducted two studies to assess the use of video in multimedia learning environments by evaluating learning, cognitive load, and social presence. The first study divided participants into two conditions, a lecture video with slides or the lecture slides with narrated audio and no video. This study found a significant difference in cognitive load, especially in the group that watched the video. The second study also divided participants into two groups, the video and no video condition. However, they collected background knowledge and visual/verbal learning preferences before studying. This study revealed that students who preferred low visual learning experienced higher cognitive load during the video condition, while those who preferred high visual learning had higher cognitive load during the no video condition.[9]

2.5. Concept maps

Joseph D. Novak created the idea of concept mapping, suggesting that meaningful learning occurs when new concepts and ideas are integrated into existing cognitive structures. Concept maps are visual knowledge representations composed of nodes and links that demonstrate the relationship (links) between the concepts (nodes). These maps can be used for various purposes such as brainstorming, composing complex structures, explaining complex ideas, and helping to learn by integrating new and prior knowledge. Some of their benefits include easy and quick recognition, and usage of minimal text that facilitates scanning of words, phrases, and main ideas. Finally, they are easier to understand and convey meaning rather than just words. Along with technological advancement, the creation of various software to design concept maps has been developed. The use of computers for creating concept maps holds more advantages such as its ease of adding, deleting, and making additional changes. They also allow automatic dynamic linking and conversion of different files, as well as enable quick and reliable communication and digital storage.[16] Yousoof *et al.*[17] suggested using concept maps to learn complex tasks such as computer programming. They developed a prototype where users could type in the program editor window and simultaneously a concept map would be created in the program. Using concept maps for learning is beneficial for encouraging explanation and reflection, which enhances critical thinking.[18]

2.6. Mobile learning through apps

Traditional learning has changed with the emergence of electronic learning (e-learning) and mobile learning (m-learning). The growing use of smartphones and tablets in the population makes it possible to enhance learning and motivation in education. Mobile devices allow learning to extend outside of traditional classroom settings by giving users the ability to obtain and share information, collaborate, access educational content, and obtain help anywhere at any time.[11,19] Mobile learning is a comfortable and effortless way of learning that can distribute the cognitive load more efficiently.[11]

Mobile devices have various motivational benefits such as freedom, ownership, communication, enjoyment, and accessibility. Mobile learning gives students more autonomy and encourages more participation in their learning. Self-determination theory (SDT) claims that students have three psychological needs: autonomy, competence, and relatedness. When these needs are satisfied, it results in psychological well-being. In turn, this satisfaction is needed for intrinsic motivation. Two types of motivation are alluded to in the SDT: autonomous and controlled. Autonomous motivation is a result of determination and self-approval, whereas controlled motivation is triggered by rewards, punishments, or introjection.[20]

Various studies have examined the use of mobile learning techniques in classrooms to reduce cognitive load. Conventionally, biology students have relied on textbooks to identify species in their field and courses. However, a study developed a mobile application, Arts App, to assess students' intrinsic motivation, perceived competence, and achievement compared to the traditional textbook.[20] They divided the students into two groups: the experiential conditions with the app and the control group with the textbook. The findings revealed that the group who used the app had higher intrinsic motivation, perceived competence, and achievement, unlike the control group. The results aligned with the SDT, suggesting that students do better when they are driven by interest, given the options, and feel in control because these factors satisfy their need for autonomy, competence, and connection. In addition, features such as interest, choice, and feedback, which are already integrated into apps unlike textbooks, account for the higher frequency of positive outcomes in the group using the app. These findings suggest that biology instructors can leverage mobile application tools to increase students' motivation and help consolidate their accuracy in species identification.[20]

A study on elementary school students examined the use of mobile learning systems and guidebooks to learn about plants. The results found a statistically significant impact on students' attitudes toward plant learning when using mobile learning systems.[20] Another study on physiotherapy students also assessed the use of mobile applications and traditional teaching sessions for learning manual therapy.[20] Their findings showed that students who used the mobile app had higher scores in a post-experimental test.[20] McMullan developed an app to help struggling medical students with calculating medical dosages.[21] The app was designed to reduce cognitive load when making calculations and was intended to be used by both students and professionals. The results revealed that participants' ability to calculate increased and they were comfortable calculating dosages. In addition, participants also had a positive attitude toward the app and indicated that the app effectively supported their learning.[21] Zhonggen *et al.*[22] also developed an app to assess if it could efficiently increase the learning of the English language, provide satisfaction, and reduce cognitive load. The results found that participants who used the mobile app had higher learning outcomes, higher satisfaction, and reduced cognitive load. Various reports in the educational field also emphasize that the integration of digital competence in education is essential for future employability and knowledge acquisition.[20]

At present, there is a lack of research on apps that help alleviate cognitive load associated with calculating building codes. While building codes are complex and multifaceted, requiring a thorough understanding to ensure compliance, the development and evaluation of tools that simplify these calculations remain underexplored. This lack of research hinders the creation of user-friendly, efficient solutions tailored to the needs of designers, leaving them reliant on traditional, often manual methods that can be time-consuming and error-prone. Addressing this gap could lead to innovative applications that streamline the design process, improve accuracy, and enhance productivity in the building design industry.

3. Research methods

3.1. Research design

This study employed a survey design to test the hypothesis that the Building Code Calculator App would facilitate students' progression through the different cognitive levels of Bloom's Taxonomy and reduce their stress levels when working on building code calculation tasks. A mixed-methods approach was used, combining both quantitative and qualitative data to assess the outcomes on information retention, cognitive performance, and stress reduction.

3.2. Participants

A convenience sample of 19 undergraduate senior interior design students from a CIDA-accredited program at a large public university in the Southwest United States voluntarily participated in this IRB-approved study. Informed consent was obtained from all participants, and the study ensured the confidentiality of their responses. Participants were made aware that their participation was voluntary and that they could withdraw from the study at any time without penalty. Participants received extra course credit for their involvement in this study.

3.3. Instrumentation

The questionnaire developed used a combination of five-point Likert scale items and open-ended questions to capture a range of responses and insights as shown in Table 1. The first two questions (Q1 + Q2) were about the participants' perceptions of the importance of building code to designers. The next two questions (Q3 + Q4) were about the participants' perceptions of their familiarity and experience with the building code. The fifth question (Q5) was about their perception of learning building code content in a design studio. Questions numbered six to eleven (Q6 – Q11) were used to assess participants' perception of their knowledge and skills based on Bloom's Taxonomy. These items were designed to assess cognitive skills across different levels of learning, from basic knowledge to higher-order thinking. It included questions aligned with Bloom's six levels: 1 – Remembering, 2 – Understanding, 3 – Applying, 4 – Analyzing, 5 – Evaluating, and 6 – Creating. The instrument was structured to assess participants' perception at each cognitive level. Questions numbered twelve to seventeen (Q12 – Q17) were based on Diffusion of Innovation Theory and were included to assess how individuals adopt new technologies. It measures factors influencing adoption, including perceived attributes such as 1 –

Table 1. Study questionnaire

#	Questionnaire items	Items classification
1	Understanding building codes should be important to interior designers.	Items to assess students' perception about building code
2	Ensuring that interior design solutions comply with building codes should be important to interior designers.	
3	I am familiar with the International Building Code.	
4	I have experience using the International Building Code.	
5	I would rate the importance of learning about building code in Interior Design Studio	
6	I can remember (recall, recognize, or identify concepts) building codes content provided through the Building Codes Calculator App.	Items based on Bloom's Taxonomy
7	I can understand (comprehend the meaning and explain in my own words) building codes content provided through the Building Code Calculator App.	
8	I can apply (use or apply knowledge in practice or real-life situations) building codes content provided through the Building Code Calculator App.	
9	I can analyze (interpret elements and structure relationships between individual components) building codes content provided through the Building Code Calculator App.	
10	I can evaluate (assess the effectiveness of whole concepts in relation to other variables) building codes content provided through the Building Code Calculator App.	
11	I can create a new point-of-view (display creative thinking and develop new concepts or approaches) based on building codes content provided through the Building Code Calculator App.	
12	The Building Code Calculator App enables me to accomplish my tasks more quickly.	Items based on the Diffusion of Innovation Theory
13	Using the Building Code Calculator App fits into my work style.	
14	Overall, I believe that the Building Code Calculator App is easy-to-use.	
15	The results of using the Building Code Calculator App are apparent to me.	
16	I was permitted to use the Building Code Calculator App on a trial basis long enough to see what it can do.	
17	I plan to use the Building Code Calculator App in the future.	
18	I would rate my stress level while working on the first exercise	Items to assess students' stress levels as they work on building code calculations
19	I would rate my stress level while working on the first exercise with the help of the Building Code Calculator App	
20	I would rate my stress level while working on the second exercise	

Relative advantage, 2 – Compatibility, 3 – Complexity, 4 – trialability, 5 – Result demonstrability, and 6 – Their intention to adopt this technology in the future. This instrument was used to predict adoption rates, identify barriers, and guide strategies to accelerate the diffusion of innovations. Questions numbered eighteen to twenty (Q18 – Q20) were related to the participants' perceptions of their stress levels during the different building code tasks. Demographic information, such as age, gender, and prior academic performance, was also collected to examine potential differences between participants.

3.4. Procedure

As shown in Figure 1, after signing the consent form, participants were provided with a building code scenario in which they were asked to calculate the occupant load for a given space. They first solved the scenario using traditional methods and then used the Building Code Calculator App. Participants were then provided with another building code scenario, and they were asked to solve it using only the Building Code Calculator App, as shown in Figure 2. The Building Code Calculator App was designed according to the cognitive load theory of multimedia to eliminate irrelevant visual information to reduce cognitive load and allow students to learn how to use the tool to calculate building code requirements. Furthermore, the idea of concept mapping was taken into consideration with a simple and easy-to-follow design that helped students navigate to complete calculations. The app automatically makes the calculations after users plug in the required information, such as sq ft., giving accurate calculations and reducing mistakes that occur when calculating codes manually. After completing all the building code tasks, participants were asked to respond to the online survey. Data were collected through the Qualtrics online survey tool that ensured anonymity and ease of access. The entire process took approximately 40 min per participant.

3.5. Data analysis

The study gathered data through an online survey. To analyze the quantitative data, descriptive and statistical analyses were performed. Statistical analyses such as the one-sample Wilcoxon test and the one-sample z-test were performed using SPSS. The one-sample median test was used to compare a hypothesized median value with the observed median value in a representative sample.

4. Results

Responses to questions about participants' demographics were analyzed through descriptive analysis. Table 2 presents participants' gender, age, race, and grade in the

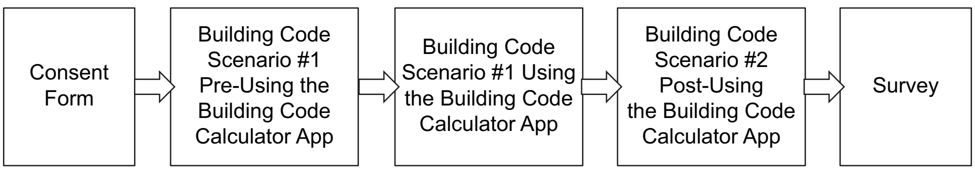

Figure 1. Study procedure

Figure 2. One of the participants using the Building Code Calculator App

interior design department. Most participants were females with ages ranging from 18 to 29. More than half of the participants are White, with the remaining identifying as other racial groups or multiracial. Over half of participants receive grade A+ or A, with 37% receiving A- or B+, while only 10% receiving grades below B+.

About 89% of the participants strongly agreed/agreed that understanding the building code should be important to interior designers and ensuring that interior design solutions comply with the building code should be important to interior designers, while about 11% strongly agreed with these two statements, as shown in Figure 3. Figure 4 shows the different levels of participants' familiarity and experience with building code.

Figure 5 shows that all participants expressed that learning about building code in the interior design studio is extremely important or important.

Table 2. Participants' demographics (*n*=19)

Sample characteristics	*n*	%
Gender		
Female	18	95
Male	1	5
Age		
Under 18	0	0
18 – 23	12	63
24 – 29	6	32
30 or older	1	5
Prefer not to answer	0	0
Race		
American Indian or Alaska Native	2	11
Asian	0	0
African American	1	5
Native Hawaiian or other Pacific Islander	0	0
White	13	68
Multiracial	2	11
Prefer to not answer	1	5
Grades		
A + or A	10	53
A- or B+	7	37
B	1	5
B- or C+	1	5
C, C-, or lower	0	0
Prefer not to answer	0	0

Note: Participants who specified more than one race were placed in the multiracial category. One participant identified as African American and American Indian. The other multiracial participants identified as Asian and White.

Figure 6 reveals that about 89% of participants agree or strongly agree that the Building Code Calculator App helped them to remember and understand the building code's content, while about 11% of participants disagreed with these two statements. It also shows that all participants agree or strongly agree that the Building Code Calculator App helped them to apply the building code's content. It also shows that about 68% of participants agree or strongly agree that the Building Code Calculator App helped them to analyze the building code's content. Figure 6 also reveals that about 74% of participants agree or strongly agree that the Building Code Calculator App helped them to evaluate the building code's content. Furthermore, it shows that about 89% of participants agree or strongly agree that the Building Code Calculator App helped them to create a new point of view based on the building code's content.

Figure 7 shows that all participants agree or strongly agree that the Building Code Calculator App enables them to accomplish their tasks more quickly (relative advantage), fits into their work style (compatibility), and is easy to use (complexity); the results of using the Building Code Calculator App are apparent to them (result demonstrability); and they plan to use the Building Code Calculator App in the future.

Participants' perceptions of their stress levels as they worked on the building code scenarios are captured in Figure 8. About 26% of the participants indicated high or extremely high levels of stress, while about 42% were neutral, and about 32% indicated low or extremely low levels of stress while working on the first building code exercise using the traditional methods. About 32% of the participants indicated high or extremely high levels of stress, while about 16% were neutral, and about 52% indicated low or extremely low levels of stress while working on the first building code exercise using the Building Code Calculator App. About 21% of the participants indicated high or extremely high levels of stress, while about 16% were neutral, and about 63% indicated low or extremely low levels of stress while working on the first building code exercise using the Building Code Calculator App. Table 3 demonstrates the mean and standard deviation of stress levels for each phase, indicating a gradual decrease in stress levels as participants used the app and during the second exercise.

Table 3. Stress level mean and standard deviation

Phase	Mean	Standard deviation
Before using the app	2.95	0.97
While using the app	2.68	1.57
After using the app	2.53	1.22

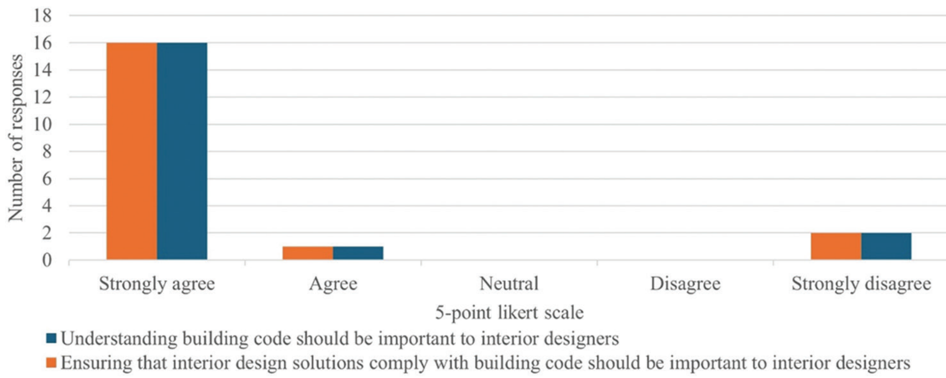

Figure 3. Bar chart representing the responses to questions related to the importance of building code to interior designers

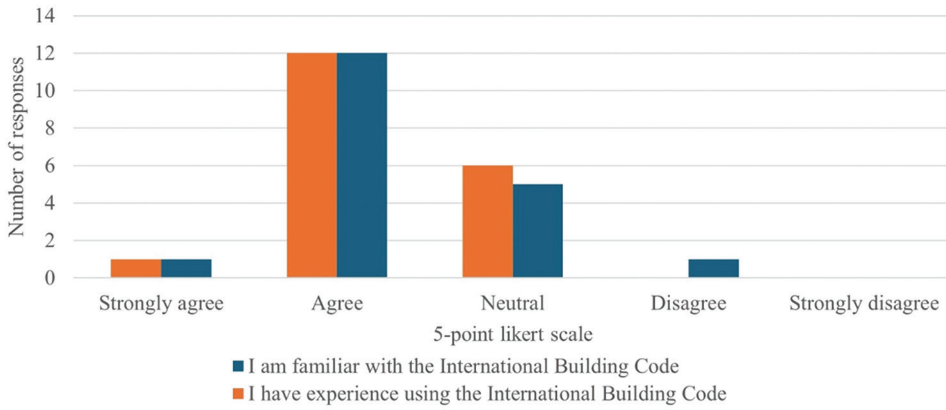

Figure 4. Bar chart representing the responses to questions related to the participants' familiarity and experience with building code

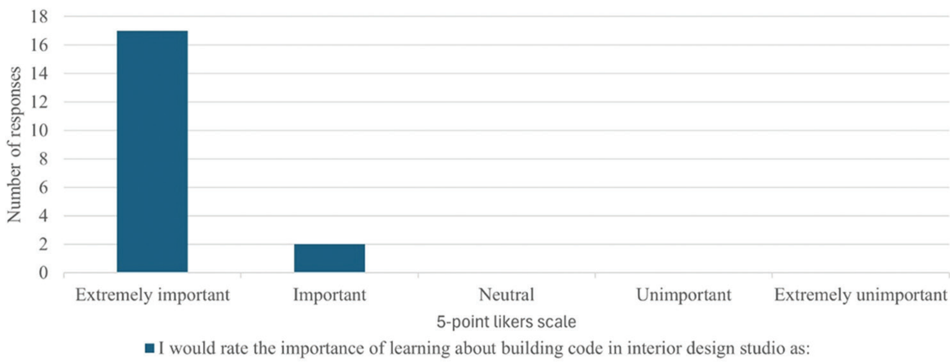

Figure 5. Bar chart representing the responses to question related to the importance of learning about building code in interior design studio

Table 3 shows the means and standard deviation for questions 18, 19, and 20. The results indicate that before using the app, the average score was relatively high, with low variability, indicating a consistent baseline among participants. While using the app, the average score decreased slightly, and the variability increased, suggesting mixed experiences during app use. After using the app, the average score further decreased, but variability reduced compared to during app use, implying more agreement in responses and generally lower stress levels compared to the pre-app usage phase.

A one-sample Wilcoxon test was conducted on questions 1 – 20, and the results are displayed in Tables 4 and 5. The hypothesis median value was set to 3. The results revealed that questions 1 – 17 had a $P < 0.05$, rejecting the null hypothesis, therefore suggesting that the observed median value is significantly different from the hypothesized

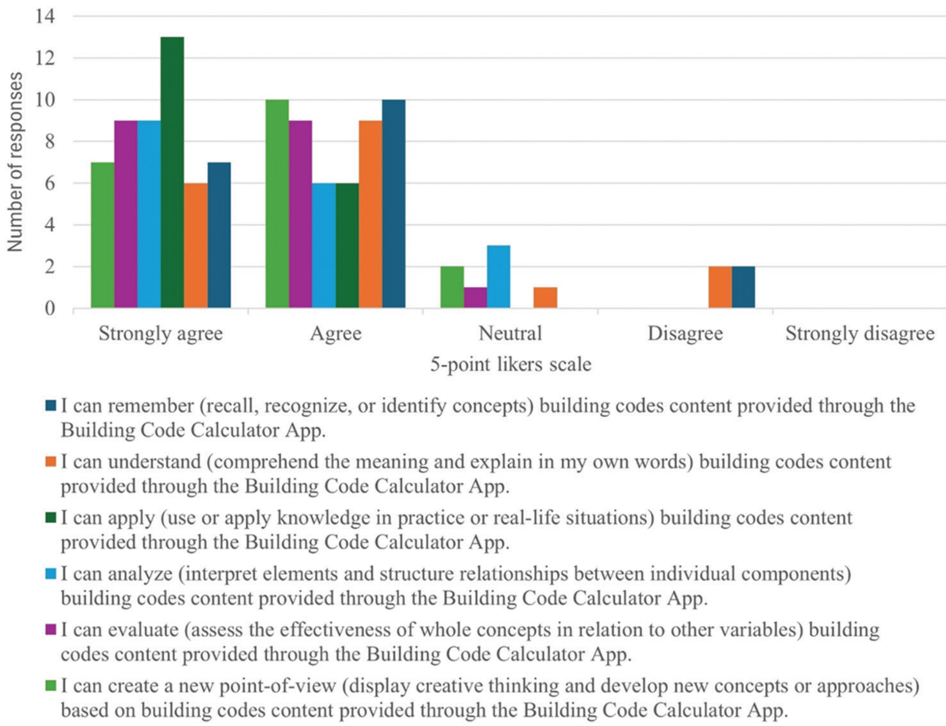

Figure 6. Bar chart representing the number of responses related to bloom's taxonomy

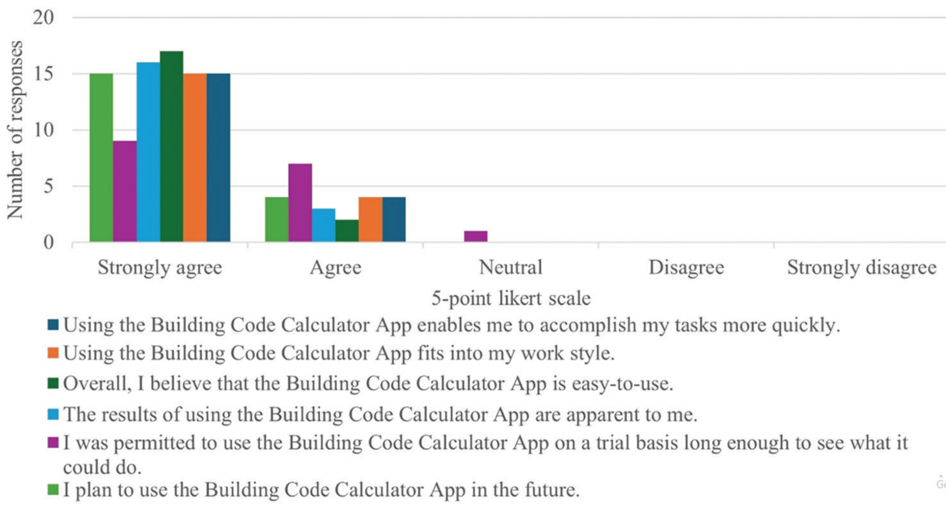

Figure 7. Bar chart representing the number of responses related to the innovation diffusion theory

median. While questions 18 – 20 had a $P > 0.05$, failing to reject the null hypothesis, thus indicating that there is no significant difference between the observed median and the hypothesized median.

Questions 21 and 22 were open-ended, and qualitative data were analyzed to find themes. Question 21 asked the participants to reflect on their experience with the Building Code Calculator App. Table 6 shows two categories of emerged themes relating to the traditional manual method of calculating building codes and themes related to the app. The themes about manual building codes were mainly negative, while themes related to the app were positive. Question 22 asked participants to reflect on their building code knowledge. Table 7 reveals that most participants expressed that they lacked knowledge of building codes and that they had rarely been exposed to this information

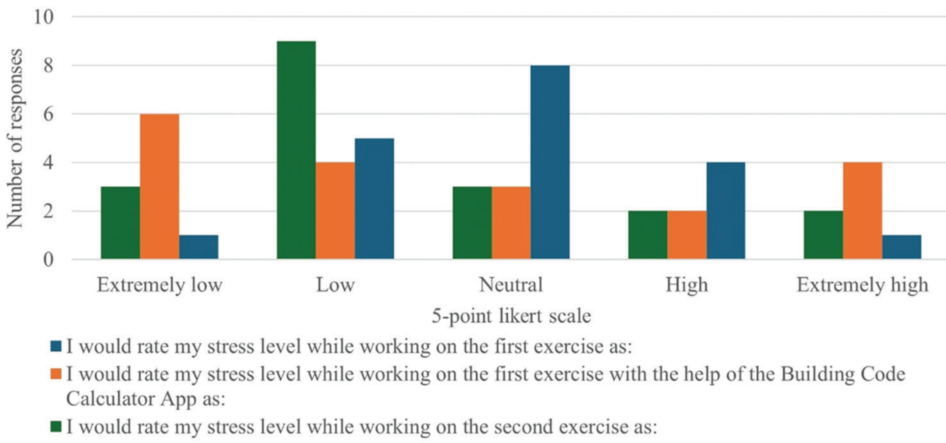

Figure 8. Bar chart representing the number of responses to participants' perception of stress levels

Table 4. One-sample Wilcoxon signed rank hypothesis test

Question	Null hypothesis	*P*
1	The median of *understanding building codes should be important to interior designers* equals 3.	<0.001
2	The median of ensuring that *interior design solutions comply with building codes should be important to interior designers* equals 3.	<0.001
3	The median of *I am familiar with the International Building Code* equals 3.	0.002
4	The median of *I have experience using the International Building Code* equals 3.	<0.001
5	The median of *I would rate the importance of learning about building code in Interior Design Studio as…* equals 3.	<0.001
6	The median of *I can remember (recall, recognize, or identify concepts) building codes content provided through the Building Codes Calculator App* equals 3.	<0.001
7	The median of *I can understand (comprehend the meaning and explain in my own words) building codes content provided through the Building Code Calculator App* equals 3.	0.002
8	The median of *I can apply (use or apply knowledge in practice or real-life situations) building codes content provided through the Building Code Calculator App* equals 3.	<.001
9	The median of *I can analyze (interpret elements and structure relationships between individual components) building codes content provided through the Building Code Calculator App* equals 3.	<0.001
10	The median of *I can evaluate (assess the effectiveness of whole concepts in relation to other variables) building codes content provided through the Building Code Calculator App* equals 3.	<0.001
11	The median of *I can create a new point-of-view (display creative thinking and develop new concepts or approaches) based on building codes content provided through the Building Code Calculator App* equals 3.	<0.001
12	The median of *using the Building Code Calculator App enables me to accomplish my tasks more quickly* equals 3.	<0.001
13	The median of *using the Building Code Calculator App fits into my work style* equals 3.	<0.001
14	The median of *overall, I believe that the Building Code Calculator App is easy-to-use* equals 3.	<0.001
15	The median of *the results of using the Building Code Calculator App is apparent to me* equals 3.	<0.001
16	The median of *I was permitted to use the Building Code Calculator App on a trial basis long enough to see what it can do* equals 3.	<0.001
17	The median of *I plan to use the Building Code Calculator App in the future* equals 3.	<0.001
18	The median of *I would rate my stress level while working on the first exercise as…* equals 3.	0.813
19	The median of *I would rate my stress level while working on the first exercise with the help of the Building Code Calculator App as…* equals 3.	0.422
20	The median of *I would rate my stress level while working on the second exercise as…* equals 3.	0.131

Note: The significance level of $\alpha = 0.05$.

throughout their education. Few participants were more knowledgeable on the subject and had experience from their previous internships, but they still struggled with conducting calculations and feeling confident. However,

Table 5. One-sample Wilcoxon signed-rank test

Question	Total (n)	Test statistic	Std. error	Standardized test statistic	Asymptotic significance (2-sided test)
1	19	169.000	22.279	3.321	<0.001
2	19	169.000	22.279	3.321	<0.001
3	19	98.000	14.431	3.153	0.002
4	19	91.000	13.000	3.500	<0.001
5	19	190.000	22.702	4.185	<0.001
6	19	177.000	23.974	3.420	<0.001
7	18	141.000	20.356	3.169	0.002
8	19	190.000	23.825	3.987	<0.001
9	18	120.000	17.048	3.520	<0.001
10	19	171.000	22.299	3.834	<0.001
11	19	153.000	20.460	3.739	<0.001
12	19	190.000	23.372	4.065	<0.001
13	19	190.000	23.372	4.065	<0.001
14	19	190.000	22.702	4.185	<0.001
15	19	190.000	23.065	4.119	<0.001
16	17	136.000	18.762	3.624	<0.001
17	19	190.000	23.372	4.065	<0.001
18	19	30.500	10.553	-0.237	0.813
19	19	83.000	18.682	-0.803	0.422
20	19	96.000	18.547	-1.510	0.131

Note: The significance level of $\alpha = 0.05$, test value=0.5.

after this study intervention that took place during their studio course, they gained more exposure and knowledge and felt more confident in building code knowledge and skills.

5. Discussion

The results of this study highlight several important findings regarding the significance of understanding building codes in design and the effectiveness of the Building Code Calculator App as a learning and application tool. First, on the importance of building code knowledge, a significant majority of participants agreed that understanding building codes and ensuring compliance is essential for interior designers. This consensus underscores that the critical role building code knowledge plays in the professional responsibilities of interior designers. Furthermore, all participants emphasized the importance of learning about building codes in the interior design studio, suggesting that integrating building code education into studio courses is vital for preparing students for professional practice. Second, on the familiarity and experience with building code, despite the recognized importance, the results revealed varying levels of familiarity and experience with building codes among participants. Many expressed limited exposure to building codes throughout their education, highlighting a gap in the curriculum. However, the study intervention improved participants' familiarity and confidence with building code content and applications, as reflected in their qualitative feedback.

Third, on the apps' effectiveness, the Building Code Calculator App proved to be a valuable tool in enhancing participants' understanding and application of building code content. Most participants agreed that the app helped them remember, understand, and apply building code content. In addition, about two-thirds of participants felt that the app supported their ability to analyze building codes and agreed that it aided in evaluating the codes. Notably, the majority indicated that the app helped them create new perspectives based on the building code content. Participants also rated the app highly in terms of usability and future intentions to use it. All participants agreed that the app enabled them to accomplish tasks more quickly, fit well with their work style, was easy to use, and provided apparent results. These findings align with the perceived relative advantage, compatibility, and complexity dimensions of the app, supporting its integration into design settings. Fourth, regarding reduction in stress levels, the app also positively influenced participants' stress levels when working on building code exercises. Traditional methods were associated with higher stress levels, with about one-fourth of participants reporting high or extremely high levels of stress. In contrast, when using the app, fewer participants reported high stress levels, and the majority indicated low or extremely low stress levels. This stress reduction suggests that the app provides a more user-friendly and efficient approach to understanding and applying building code.

The one-sample Wilcoxon test indicated that most quantitative survey items (Questions 1 – 17) had a significant difference from the hypothesized median, reinforcing the positive impact of the app on participants' learning experiences. Open-ended responses further highlighted the contrast between the traditional manual methods and the app. Themes related to traditional methods were predominantly negative, focusing on challenges such as difficulty and inefficiency. Conversely, themes related to the app were overwhelmingly positive, citing its ease of use, ability to simplify calculations, and overall effectiveness. These findings suggest a pressing need to enhance building code education within design programs. Participants' reflections indicate that limited exposure to building codes during their education contributes to a lack of confidence

Table 6. Themes related to Question 21

Variable	Definition	Example
Manual building code themes		
Confusion	Lack of understanding, unclear	"The manual can get confusing and may cause issues for miscalculations and misinformation when doing the occupancy wrong."
Struggle/Hard/Difficult	Task requires excessive amount of effort to complete or achieve	"Personally, deciphering building codes and figuring calculations such as occupant load has always been something I struggled with."
Stressful/Overwhelming	Intense situation become difficult to manage and lead to mental or emotional strain	"Sometimes it can be overwhelming to remember everything we need to know to do occupancy loads."
Inaccurate/Miscalculation/Wrong	Not correct, information contains errors and is misleading	"May cause issues for miscalculations and misinformation when doing the occupancy wrong."
Negative emotions	Unpleasant feelings	"I have always been very insecure about my knowledge of international building codes and calculations."
Building Code App themes		
Easy/User-friendly	Simple and does not require a lot of effort to complete	"I think that the building code app was a very efficient app that is user-friendly and easy to navigate."
Fast/Time	Completed quickly	"I would say that using the building code app significantly cut down the amount of time it took me to complete the exercise."
Helpful/Beneficial/Useful	Makes task easier to complete	"Helpful for new graduates that are unfamiliar with building codes."
Accurate calculations	Correct answer that is error-free	"The app would help eliminate the issues and provide accurate answers."
Stress-free	Condition of being calm and relaxed	"I feel like it took all of the stress out of determining what each occupancy type was."
Positive emotions	Pleasant feelings of happiness	"I thoroughly enjoyed being able to actually see the apparent outcome of an app such as this during the study."
Design/Graphics	Visuals that communicate information	"The graphics that accompanied the texts made it quicker to know which section to navigate."
Future/Career	A period that has not occurred where a professional occupation will take place	"This app gives me hope that I can use this in my future career to save time and energy."

Table 7. Themes related to Question 22

Variable	Definition	Example
Building code knowledge		
Occupancy classification	Categorization of building or space based on its function	"The occupancy classification is the type of structure you are working on such as education, assembly, business, etc."
Occupancy factor	Amount of space needed per person in a space	"The occupancy factor is the amount of sq ft that is allotted to a person."
Occupancy load	Amount of people that can be safely accommodated in a building	"The occupant load is the amount of people that can be in a space at once."
Water closets	Room with a toilet	"In the building codes, we can also learn about the how many water closets you can have in a space depending on the size of the area."
Means of egress	Pathways for people to safely exit a building	"The means of egress is the path of which a person would take during an evacuation."
ADA compliance	American Disability Act that ensures disables users have equal access to buildings	"I also have a good foundation for codes regarding ADA compliance."
Calculations/Handbook	Solving numerical problems with the use of a manual guide	"I very much still heavily rely on the IBC book when it comes to figuring calculations out, and it does take me quite the minute to flip through it."
Lack of knowledge	Insufficient understanding about a topic	"My building code knowledge is not great. I find it is hard to understand and I try to avoid it at all costs."

(Cont'd...)

Table 7. *(Continued)*

Variable	Definition	Example
Negative Feelings	Unpleasant emotions	"I have always felt uncertain about occupancy classification and load. This is actually what I am most nervous about for onboarding to my new place of work in the industry."
Interior design educational curriculum		
Lack of emphasis/ enforcement	Insufficient importance is given to a subject	"I would like to know more but it makes it difficult when it is not emphasized early into the program."
Emphasis needed	Give more attention to a subject	"I think an earlier emphasis on codes would have helped me understand things such as occupancy loads and egress a lot better."
Interior design studio		
Gained knowledge/ understanding	Enhancement of information or skill	"My building code knowledge has developed the most during Studio VI. Before this year, I did not know much about building codes. After our class lectures, I feel very knowledgeable in means of egress and occupancy classifications."
Practice codes	Repeated application of skills to improve ability	"Studio VI is helpful in terms of getting to practice the codes in our project."
Increased confidence	Belief in one's ability	"After taking the capstone studio course I have felt much more confident in knowing where to look to find the answers I need using our course content material."

Abbreviations: ADA: American disability act; IBC: International building code®.

and preparedness. Integrating tools like the Building Code Calculator App into studio courses can bridge this gap by providing practical, hands-on learning opportunities that improve understanding, reduce stress, and enhance confidence in building code applications.

6. Conclusion

This study underscores the critical importance of building code knowledge in design education and practice while demonstrating the potential of innovative tools like the Building Code Calculator App to address existing gaps in the curriculum. The findings reveal that while building code knowledge is widely recognized as essential, many participants lack sufficient familiarity and experience with it due to limited exposure during their education. However, the integration of the Building Code Calculator App into learning environments significantly enhanced participants' understanding, confidence, and ability to apply building code concepts effectively. The app's usability, efficiency, and ability to reduce stress associated with traditional methods were consistently highlighted, making it a valuable addition to design studio courses. These results advocate for a more comprehensive approach to building code education that leverages technology to provide practical, hands-on learning opportunities. By bridging the gap between theoretical knowledge and practical application, such tools can better prepare students for professional responsibilities, fostering both competence and confidence in building code applications.

This study has several limitations that warrant consideration and provide directions for future research. First, the low number of survey participants limits the generalizability of the findings, and future studies should aim to include a larger and more diverse sample to validate these results. Second, participants had limited time to explore and use the Building Code Calculator App, which may have constrained their ability to fully understand and utilize its features. Extending the study duration would allow for a more comprehensive evaluation of the app's long-term impact on learning and application. Finally, while this study focused on participants' perceptions of the app, it did not examine the correlations between these perceptions and their actual performance on building code tasks. Future research should explore this relationship to determine whether positive perceptions of the app translate into measurable improvements in performance, providing a deeper understanding of its effectiveness as an educational tool.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Hebatalla Nazmy
Formal analysis: All authors
Investigation: Hebatalla Nazmy
Methodology: Hebatalla Nazmy
Writing – original draft: All authors
Writing – review & editing: Hebatalla Nazmy

Ethics approval and consent to participate

This study was approved by the Oklahoma State University Institutional Review Board (IRB) under the application number IRB-22-30. The IRB granted approval on January 24, 2022, and processed the application as expedited. Human subjects were involved in this study, and written consent was obtained from all participants, ensuring their informed participation.

Consent for publication

Human subjects were involved in this study, and written consent was obtained from all participants, ensuring their informed participation and permission was obtained from each of the subjects to publish their data and/or images.

Availability of data

Not applicable.

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ARTICLE

Experimental and numerical analysis of 3D-printed objects based on oriented anisotropic cells

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Abstract

The use of additive manufacturing technology has grown significantly in recent years, creating new challenges for product designers. Complex designs are rarely fully described in traditional drawings or design specifications. This research aimed to address this gap by developing specifications based on the mechanical characterization of fused deposition modeling objects, focusing on their anisotropic behavior as influenced by cell structures. We used experimental design, analytical research using finite element methods, statistical analysis, and simplified numerical models to investigate the relationship between mechanical characteristics and manufacturing factors. The main effects of building attributes were examined in addition to formulating failure mechanisms and generalized elasticity. The findings allowed the creation of a simplified model to describe mechanical behavior by demonstrating the relationship between infill methods and mechanical strength.

Keywords: Additive manufacturing; Finite element method; Anisotropic cells; Design

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1. Introduction

Over the past few years, 3D printing technologies, or additive manufacturing, have begun to take center stage in a number of market sectors. This could be a result of low-cost technologies, which are mostly fused filament fabrication (FFF) technologies, becoming more widely employed.[1,2]

Despite this remarkable popularization, a number of obstacles still need to be addressed, and a number of manufacturing and product-related problems have come to light. Among these issues, mechanical anisotropy of the material directly influences mechanical strength, potentially endangering functional components.[3,4]

Several studies have been done to better understand the anisotropic behavior of FFF objects and fabrication parameters. For example, Ahn *et al.*[5] first experimentally described the main effects of fused deposition modeling as a function of the air gap, bead width, color, temperature, and orientation. This work evidenced the main contribution of each component to the strength of the object. In addition, Domingo-Espin *et al.*[6] presented the identification of the compliance matrix as a function of basic fabrication orientation. On the other hand, there are studies of the damage and failure mode of FFF objects under severe compression.[4,7] This approach was also adopted by several other studies.[8-21] For example, Li and Wang[22] studied the mechanical behavior of 3D printing sandwiches against bending load. Many studies also indicated the effect of process parameters on anisotropic behavior.[4,5,23,24]

However, there are not many investigations on the connection between process parameters and the mechanical strength of FFF items in a computational environment to support design specifications and technical drawings.

The complexity of objects and their fabrication parameters can lead to specifications that are not well-defined. For instance, in building infill strategies, identical geometries can yield objects with vastly different mechanical properties. This issue highlights a broader problem with inadequate design specifications and outdated technical drawing standards. Addressing this challenge, the primary objective of this study is to introduce a new approach for specifying additive manufacturing objects that take into account their mechanical anisotropy. The study is organized into four sections: numerical characterization, experimental characterization, development of a new specification method, and evaluation of the proposed method. The central idea is to integrate simplified anisotropic cells into 3D models and technical drawings to ensure that the final object aligns with both the specifications and simulated results. Furthermore, this approach facilitates topological optimization by creating objects based on a flexible cost function, allowing half of the mass to be produced using hexagonal cells (Figure 1).

In both theoretical and experimental studies of FFF, also known as fused deposition modeling, the normal and shear stresses and strains of objects were analyzed as functions of the primary fabrication parameters. As a result, the generalized anisotropic behavior of the material and orthotropic compliance matrices were determined based on bead orientation, air gap, layer thickness, and the type of infill strategy. Ultimately, these generalized anisotropic matrices were integrated into the 3D model and

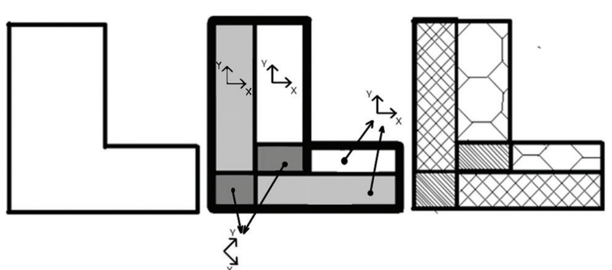


Figure 1. Schematic of the incorporation of generalized anisotropic cells in the model and its final expected result

technical drawings to constrain fabrication parameters and predict mechanical behavior without requiring intensive computational methods.

For the first two parts of this study, we established three infill strategies to be analyzed: raster (with 100% density), grid, and hexagonal infill. For each one of these infill strategies, we have applied a multivariable analysis method, where the experiment design was full (2^4 for 100% density raster and 2^3 for grid and hexagonal infill) with two levels and no central point. The control factors considered were raster orientation (α), distance between lines (d), layer thickness (h), and bead width (w) for 100% density raster. For grid infill, we established the distance between lines (d), layer thickness (h), and bead width (w) as control factors. On the other hand, hexagon diameter (hex), layer thickness (h), and bead width (w) were selected as control factors for hexagonal infill.

The main responses of this study were young modulus, Poisson ratios, maximum internal stress, and maximum equivalent stress (based on external dimensions of specimen cross-section). In addition, we identified the contribution of the control factors for a generalized orthotropic compliance matrix. This generalized matrix was developed to create a simplified numerical simulation that is both computationally efficient and easily integrated into technical specifications.

We utilized Ansys Workbench for finite element analysis, Minitab for data processing, and Matlab for numerical modeling. Experimental analysis was conducted using a universal testing machine, with strain measurements taken through strain gauges.

In the final section of this work, we present a technical specification proposal in which anisotropic cells were integrated into the object to simplify and accelerate the computational model of the object's mechanical behavior. These anisotropic cells also limit the manufacturing parameters, though the mechanical properties can still be achieved through different fabrication parameters within specific process windows.

Finally, we implemented the proposed method and compared the overall results from three approaches: detailed numerical simulation, simplified numerical simulation, and experimental outcomes.

2. Materials and methods

To properly analyze the numerical and experimental anisotropic behavior of FFF objects, we applied a 2^k multivariable methodology (full design with no central points) where raster orientation (α), line overlap (o), layer thickness (h), and bead width (w) were the control factors for 100% density raster. For grid infill, the analyzed control factors were air gap (d), layer thickness (h), and bead width (w). On the other hand, we established hexagon diameter (hex), layer thickness (h), and bead width (w) as control factors of the hexagonal infill design.

We defined the equivalent maximum permissible stress, which is based on the external dimensions of the specimen, and the maximum internal permissible stress as the responses. Furthermore, we analyzed the relative Young's modulus, Poisson's ratios, strains, normal stresses, and shear stresses to determine generalized orthotropic matrices as a function of fabrication parameters.

To compare this work with previous studies, the experiment design is presented in Table 1, where the variable levels and their values are shown.

We can also highlight that the raster orientation was not included in the experimental design, whereas the strain, stress, and admissible stresses were analyzed in all three orthotropic directions.

The core concept of these control factors is illustrated in Figure 2, which provides a schematic of the raster cross-section, explaining the significance of bead width, air gap, and layer height. The general idea of overlap and hexagon diameter are also represented in this figure. The hexagon diameter refers to the parameter that controls the shape of a hexagonal honeycomb. In this case, the hexagon is inscribed into a circle with a diameter equal to the hexagon diameter. This parameter represents a novel infill parameter, as most slicers calculate the infill based on density proportion. It is important to note that density parameters typically result in variations in infill shapes, which, in turn, produce differing anisotropic effects.

Conversely, filament overlap is a variation of the air gap that represents a negative air gap. As a result, even if the infill density is 100%, the process can vary, and slight overlaps, within acceptable limits, can result in different mechanical strengths. For the finite element analysis, we modeled the specimens and fabrication filament, replicating the key fabrication characteristics that influence mechanical anisotropy.

The material we used for analytical and experimental studies was natural ABS GP-35 (filament 1.75 mm), whose general properties are listed in Table 2. The values of the heat deflection temperature and the glass transition

Table 1. Experiment design

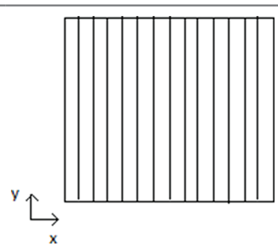
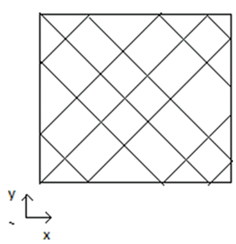
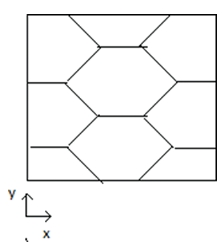
Infill type	Illustration of infill type	Process control factor	Control factors	
			Lv−1	Lv+1
Raster (100% density)		Bead width (mm)	0.4	0.5
		Line overlap (%)	0	15
		Layer height (mm)	0.15	0.2
Grid infill		Bead width (mm)	0.4	0.5
		Air gap (mm)	1	2
		Layer height (mm)	0.15	0.2
Hexagonal infill		Bead width (mm)	0.4	0.5
		Hexagon diameter (mm)	1	2
		Layer height (mm)	0.15	0.2

Table 2. General properties of natural ABS[25]

Property	Standard	Value
Tensile strength	ASTM D638	36 MPa
Young's modulus	ASTM D638	2.4 GPa
Flexural strength	ASTM D790	61 MPa
Flexural modulus	ASTM D790	2.3 GPa
Elongation at break	ASTM D638	4%
HDT 1.82 Mpa	ASTM D648	93°C

Abbreviation: HDT: Heat deflection temperature.

temperature (TG) - ASTM D7028 (−83°C) of the material indicate the thermal workability of the material.

The statistical analysis of the data was conducted using Minitab software, while external features were measured with a caliper that has a 0.01 mm resolution. Microscopic and image processing tools were employed to analyze the smaller features. To assess the mechanical strength in the layer construction direction, we utilized a universal testing machine, the EMIC DL10000. For measuring specimen displacement, strain gauges were attached to the boundaries of anisotropic cells. In addition, the standard ASTM D 638 type IV specimen shape was used to ensure comparability with existing data.

In Figure 3, one example of the internal cell orientation is presented. The orientation of construction cells was analyzed in all experiments, while six stress states were evaluated to derive the compliance matrices.

In the same way, the specimens that were used to characterize the shear state are presented in Figure 4. A direct shear test was conducted to identify the material shear strength as a function of fabrication strategy.

It is worth mentioning that we did not consider the effects of deposition temperature, environmental temperature, bed temperature, warping, or bead width variations in this study. As a result, there are at least 17 process parameters that could still influence the mechanical and geometrical properties of the object, necessitating further research to incorporate these factors into the simplified anisotropic cells method. The bead width is primarily determined by nozzle diameter, extrusion speed, layer height, and displacement speed. In addition, the nozzle height controls the layer height. It is also important to note that these parameters are not directly implemented in commercial automatic slicers, so we had to modify some internal codes in Repetier Host to achieve these results. For the finite element analysis, we used a tetrahedral mesh with a width of 0.055 mm for all virtual simulation specimens, which were also simulated in Ansys.

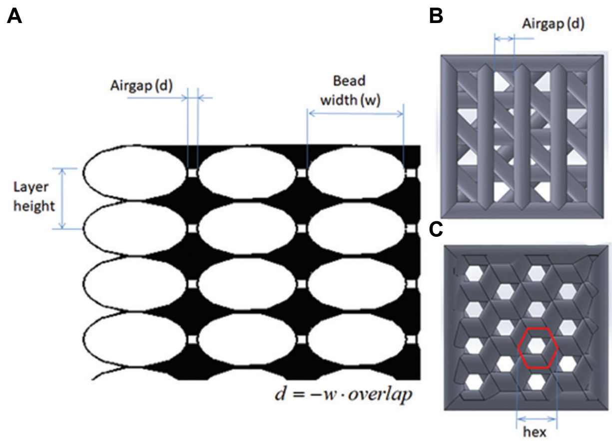


Figure 2. Schematic description of main fabrication parameters in (A) transversal cross-sectional view of raster infill; (B) top view of grid infill; and (C) top view of hexagonal infill. Air gap (d), bead width (w), layer height (h), and hexagon diameter (hex) are shown.

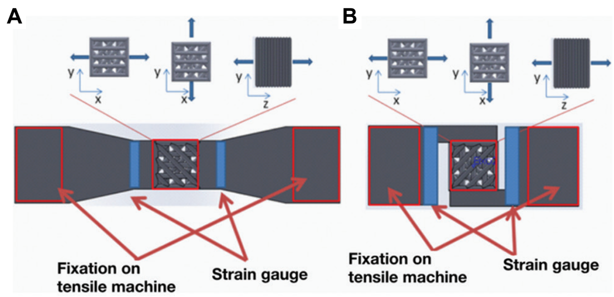


Figure 3. Example of (A) tensile specimen orientation and (B) shear specimen orientation

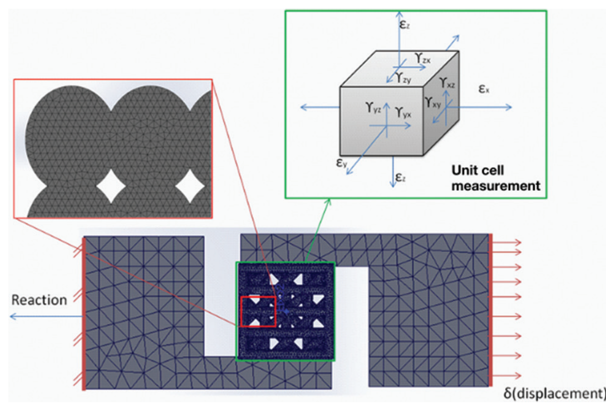


Figure 4. Schematic of mesh parameter, boundary conditions, and measurement probes for the unit cell, exemplified by the grid cell shear specimen with a bead width of 0.4 mm, a layer height of 0.2 mm, and an air gap of 1 mm.

The boundary condition applied in all the studied cases consists of a fixed constraint on the one side of the specimen and a displacement constraint on the other side.

Probes were also defined to measure reaction forces and deformations (normal and shear) of cell units as a function of the displacement. Therefore, it is possible to identify the correlation between average stresses and the deformation of cell units.

Multiple steps were applied to characterize the orthotropic elasticity and shear moduli of unit cells, with a step increment was 0.001 mm. Therefore, we can consider these studies as Dirichlet-Dirichlet problems.

It is also possible to note that the deformation in all directions (εx, εy, εz, γxy, γxz, γzy) and the maximum equivalent stress (von Mises) were acquired in each step, allowing the calculation of the elastic and shear moduli for the unit cell in each step. By the end, the average moduli were placed in the compliance matrix.

While the primary goal of this work is to determine how geometry affects material strength, leading to anisotropy, we also took into account the material's non-linear model and isotropic behavior. Table 2 describes the material's characteristics. The properties of the material are described in Table 2.

An example of solid mesh and interaction between bead and layers in a transversal cross-section is presented in Figure 5, in addition to the schematic of FEA boundary conditions. This figure also shows the schematic of unit cell measurement. With respect to failure criteria, we established yield failure based on distortion energy (von Mises), while this study investigates the anisotropic behavior of the material in the elastic state. Therefore, it is possible to correlate forces, strain, stresses, and maximum equivalent stresses (von Mises) of the unit cell.

It is important to highlight that the simulation model accounts for the elastic behavior of the material. However, further research is necessary to explore the plasticity and failure of these anisotropic cells to develop improved design specifications and more accurate models. To assess the elastic behavior of these specimens, we analyzed strain in the x, y, and z directions, as well as shear strain in the xy, xz, and yz planes, in addition to plane strain.

For analyzing Young's modulus and Poisson's ratios, load combinations were applied, and responses were measured in the notch area to generate stress-strain (S-S) diagrams.

Eventually, we determined the coefficients of the orthotropic compliance matrix, as presented in Equation I.

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_x \\ \varepsilon_x \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & \frac{-v_{xy}}{E_x} & \frac{-v_{xz}}{E_x} & 0 & 0 & 0 \\ \frac{-v_{xy}}{E_y} & \frac{1}{E_y} & \frac{-v_{yz}}{E_y} & 0 & 0 & 0 \\ \frac{-v_{xz}}{E_z} & \frac{-v_{yz}}{E_z} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \cdot \begin{bmatrix} \sigma_x \\ \sigma_x \\ \sigma_x \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} \quad \text{(I)}$$

The last part of this study introduced and implemented the 3D models and technical specifications using the simplified anisotropic cells method.

A case study object was developed and fabricated according to Figure 5, where the simplified simulation (simplified orthotropic cells), detailed simulation (3D modeling of filaments), and experimental data were analyzed and compared.

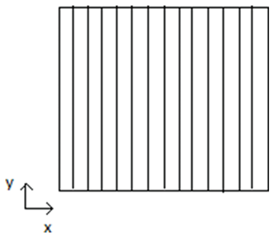
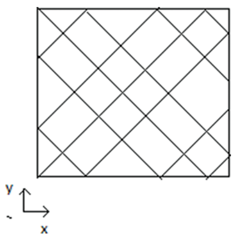
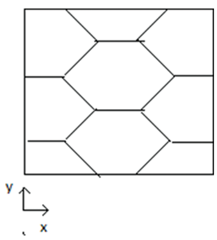
In this case, all three study cases were submitted to increasing load until the break. For the two simulations, we considered a breakpoint when the maximum object's internal stress exceeds admissible material stress.

In these study cases, we adopted fabrication parameters which are presented in Table 3. Temperature, material, and extrusion speed were kept constant.

3. Results and discussion

Based on the results obtained, we calculated the internal stresses of the specimens and compared them to the

Table 3. Fabrication parameters of case study

Infill type	Illustration of infill type	Process control factor	Control factors
Raster (100% density)		Bead width (mm)	0.4
		Line overlap (%)	15
		Layer height (mm)	0.15
Grid infill		Bead width (mm)	0.4
		Air gap (mm)	2
		Layer height (mm)	0.15
Hexagonal infill		Bead width (mm)	0.4
		Hexagon diameter (mm)	2
		Layer height (mm)	0.15

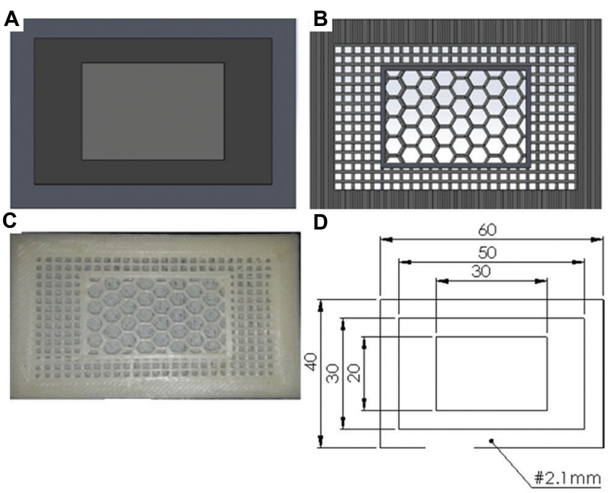


Figure 5. Case study object illustrating: (A) the simplified anisotropic cells method; (B) the detailed finite element method; (C) the fabricated physical prototype; (D) technical specification of specimen.

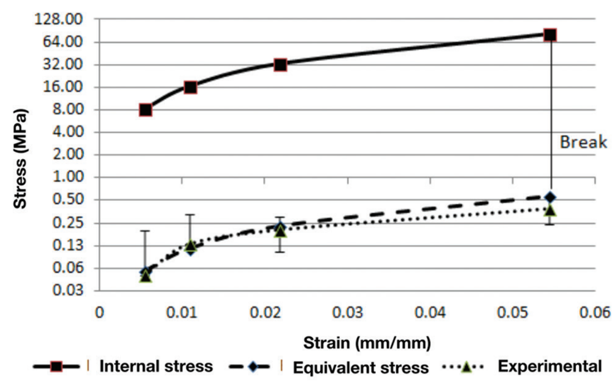


Figure 6. Example of stress-strain diagram illustrating maximum internal stress, average stress, and experimental test for grid cell type experiment 1. Fabrication parameters: bead width = 0.4 mm, layer height = 0.15 mm, and air gap = 1 mm. Test performed in the × normal direction under tensile loading.

average stresses depicted in the S-S diagram within the material's elastic range. The average stress corresponds to the outer area of the notch cross-section, effectively simulating ASTM 638 procedures in a laboratory setting.

In Figure 6, the S-S diagram of grid cell type experiment 1 is presented. The maximum internal principal stress and the average stress as a function of strain reveal a divergence that is mainly caused by the internal porosity of the specimen.

The main responses of normal and tangential stresses as a function of fabrication parameters are presented in Table 4. It is important to highlight that these results are related to external stresses. Internal stresses tend to be around 50 MPa. This finding is particularly relevant for

Table 4. Mean responses of mechanical external stress as a function of fabrication parameters

	Control factors						Mean responses (MPa)					
	Line overlap (mm)		Bead filament (mm)		Height (mm)							
	Value	Lv	Value	Lv	Value	Lv	σ Break X	σ Break y	σ Break z	τ Break XY	τ Break Yz	τ Break xz
Raster cell	0.05	−1	0.4	−1	0.15	−1	1.09	0.88	0.20	0.25	0.23	0.54
	0.05	−1	0.4	−1	0.2	1	1.36	1.07	0.21	0.26	0.29	0.51
	0.05	−1	0.5	1	0.15	−1	1.14	0.92	0.19	0.22	0.27	0.55
	0.05	−1	0.5	1	0.2	1	1.32	1.15	0.25	0.19	0.28	0.53
	0.1	1	0.4	−1	0.15	−1	1.11	0.93	0.20	0.19	0.24	0.41
	0.1	1	0.4	−1	0.2	1	1.36	1.00	0.24	0.18	0.28	0.46
	0.1	1	0.5	1	0.15	−1	1.08	0.90	0.19	0.19	0.24	0.44
	0.1	1	0.5	1	0.2	1	1.34	1.07	0.23	0.19	0.24	0.55
	0.025	0	0.45	0	0.175	0	1.20	0.78	0.21	0.15	0.21	0.51
Hexagonal cell	1	−1	0.4	−1	0.15	−1	0.24	0.17	0.06	0.25	0.06	0.05
	1	−1	0.4	−1	0.2	1	0.34	0.20	0.06	0.32	0.04	0.05
	1	−1	0.5	1	0.15	−1	0.21	0.19	0.05	0.20	0.02	0.06
	1	−1	0.5	1	0.2	1	0.21	0.19	0.11	0.21	0.07	0.12
	2	1	0.4	−1	0.15	−1	0.06	0.08	0.11	0.11	0.04	0.08
	2	1	0.4	−1	0.2	1	0.08	0.08	0.17	0.14	0.06	0.12
	2	1	0.5	1	0.15	−1	0.08	0.11	0.20	0.16	0.09	0.21
	2	1	0.5	1	0.2	1	0.11	0.14	0.21	0.22	0.07	0.18
	1.5	0	0.45	0	0.175	0	0.11	0.08	0.14	0.13	0.04	0.07
100% Full density raster	1	−1	0.4	−1	0.15	−1	0.28	0.27	0.22	0.09	0.06	0.31
	1	−1	0.4	−1	0.2	1	0.29	0.32	0.24	0.13	0.05	0.31
	1	−1	0.5	1	0.15	−1	0.28	0.28	0.23	0.11	0.06	0.46
	1	−1	0.5	1	0.2	1	0.39	0.35	0.29	0.14	0.08	0.37
	2	1	0.4	−1	0.15	−1	0.12	0.12	0.29	0.05	0.06	0.15
	2	1	0.4	−1	0.2	1	0.16	0.17	0.24	0.07	0.08	0.16
	2	1	0.5	1	0.15	−1	0.15	0.17	0.22	0.05	0.09	0.25
	2	1	0.5	1	0.2	1	0.20	0.22	0.29	0.07	0.08	0.25

designers, as it highlights the need to evaluate the actual strength of an object by considering both internal infill and external geometry.

The difference between average stress and internal stress is noticeable, primarily due to the orientation of the filaments and the presence of internal gaps. In engineering design, the equivalent stress is a crucial factor. In this case, an external stress of 0.55 MPa was used as the design criterion, corresponding to an internal stress of 50 MPa. It is worth mentioning that this case study resulted in an object with a density of 19.5%.

This analysis serves as an internal validation of the method and demonstrates its potential applicability to other scenarios. However, further studies are necessary to fully understand the potential uses of this method. Figure 7 also shows that the experimental stresses closely match the numerical equivalent stresses, supporting the method's accuracy in predicting the mechanical behavior of 3D-printed objects. This consistency was observed across all experimental results, bolstering confidence in this approach. The prediction of these values is crucial for proper specification and reliable design.

Regarding the primary effects of control parameters on the anisotropic behavior of raster cells, as shown in Figure 7, layer height was identified as the most influential factor affecting break strength in the x, y, and z normal directions.

Line overlap has the greatest impact on mechanical strength in both xz and xy shear directions.

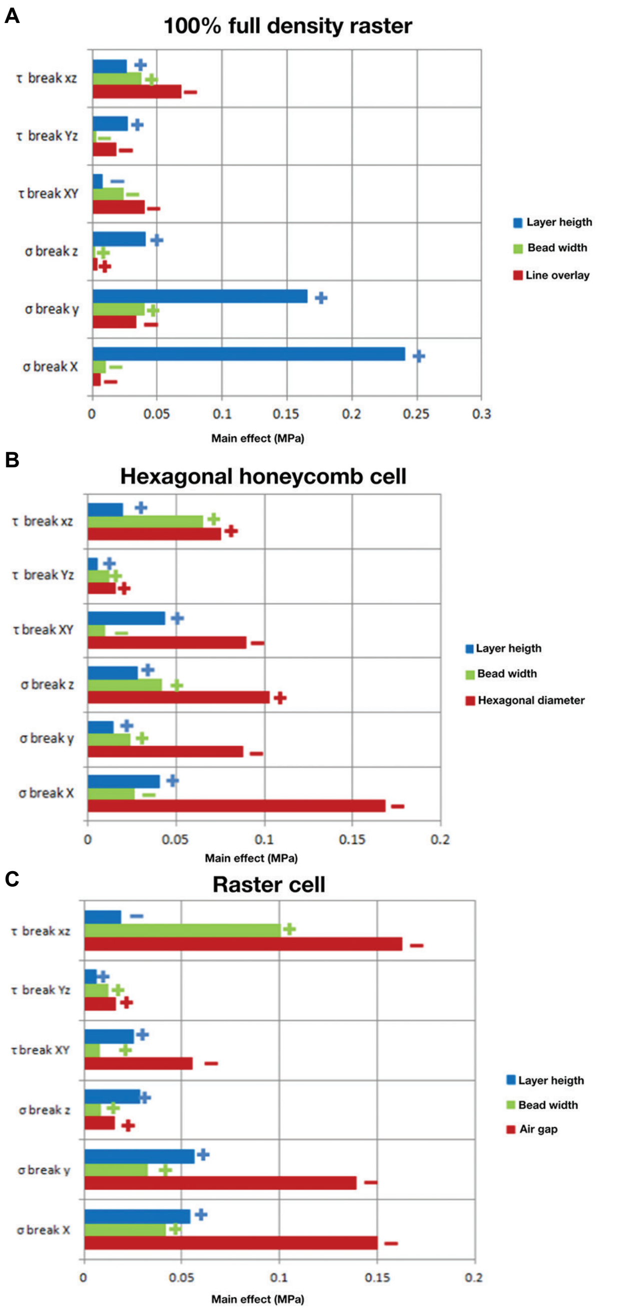


Figure 7. Main effects of normal and shear strength as a function of (A) filament overlap, layer height, and filament width; (B) hexagon diameter, layer height, and filament width; and (C) air gap, layer height, and filament width.

This is because the filaments are deposited along the y direction, acting similarly to composite fibers within the material. It is also evident that shear strength is significantly influenced by line overlap, with larger filament diameters generally leading to reduced shear strength.

It is also important to recognize that, even though slicer software may indicate a 100% density for raster cells, the physical object often contains porosities. These porosities lead to a reduction in the actual density of the object, which varies depending on the layer height and filament diameter.

In Figure 8, the contour diagram shows the overlap of parameters that leads to the best results for each response. The feasible area represents the combination of factors that produce maximum mechanical strength. Objects made with thicker layers demonstrate the highest mechanical strength, particularly when the line overlap is moderate and the bead width is high. In addition, it is evident that beyond a certain level of overlap, further increases do not significantly enhance mechanical strength. This can be attributed to the fact that, past a certain point, the porosity does not decrease significantly.

This study provides a predictive framework for understanding the mechanical behavior of objects fabricated with raster cells. It serves as a valuable tool for engineers and designers to accurately specify the mechanical strength of entire objects or specific components in technical drawings. In addition, this approach ensures consistent quality and repeatability of mechanical and dimensional properties regardless of the manufacturing site.

Regarding raster cells, we identified the linear orthotropic compliance matrix as a function of control factors, as presented in Equation II. This matrix was developed in order to create simplified finite element models that can simulate objects with variable anisotropic behavior at a low computational cost.

$$[C]=\begin{bmatrix} \begin{pmatrix} +0.2894 \\ -0.09\cdot O \\ -0.2889\cdot h \end{pmatrix} & \begin{pmatrix} +0.06005 \\ -0.0198\cdot O \\ -0.0747\cdot h \end{pmatrix} & \begin{pmatrix} -0.0038-0.01075\cdot O \\ +0.033\cdot Wd \\ +0.188\cdot h \\ -0.191.Wd\cdot h \end{pmatrix} & 0 & 0 & 0 \\ \begin{pmatrix} +0.0505 \\ -0.0789\cdot h \end{pmatrix} & \begin{pmatrix} +0.148 \\ +1.25\cdot O \\ +0.291\cdot h \\ -7.36\cdot Wd\cdot O \end{pmatrix} & \begin{pmatrix} +0.01011 \\ +0.0672\cdot h \end{pmatrix} & 0 & 0 & 0 \\ \begin{pmatrix} +0.081-0.588\cdot O \\ -0.160\cdot Wd \\ -0.507\cdot h \\ -1.302\cdot Wd\cdot O \\ +1.586\cdot Wd\cdot h \end{pmatrix} & \begin{pmatrix} +0.1085 \\ -0.471\cdot h \\ -0.265\cdot Wd \\ +1.89\cdot Wd\cdot h \end{pmatrix} & \begin{pmatrix} +0.419 \\ -2.01\cdot h \\ -0.842\cdot Wd \\ +6.19\cdot Wd\cdot h \end{pmatrix} & 0 & 0 & 0 \\ 0 & & 0 & \begin{pmatrix} -0.786 \\ +6.13\cdot h \\ .1.91\cdot Wd \\ -10.44\cdot Wd\cdot h \end{pmatrix} & 0 & 0 \\ 0 & 0 & 0 & 0 & \begin{pmatrix} +0.901-7.23\cdot O \\ -1.241\cdot Wd \\ -2.527\cdot h \\ +8.25\cdot Wd\cdot O \\ +17.53\cdot O\cdot h \\ +4.84\cdot Wd\cdot h \end{pmatrix} & 0 \\ 0 & 0 & 0 & 0 & 0 & \begin{pmatrix} -2.24 \\ +12.83\cdot h \\ -5.14\cdot Wd \\ -28.4028\cdot Wd\cdot h \end{pmatrix} \end{bmatrix} \quad (II)$$

For hexagonal cells, the main effect of control factors on mechanical strength are presented in Figure 7. In this figure, the hexagon diameter was identified as the parameter most negatively affecting the normal mechanical strength in the x and y directions. In contrast, increasing the hexagon diameter strengthens the object in the normal z direction.

This is straightforward to understand because a larger diameter of the hexagon decreases the density of the

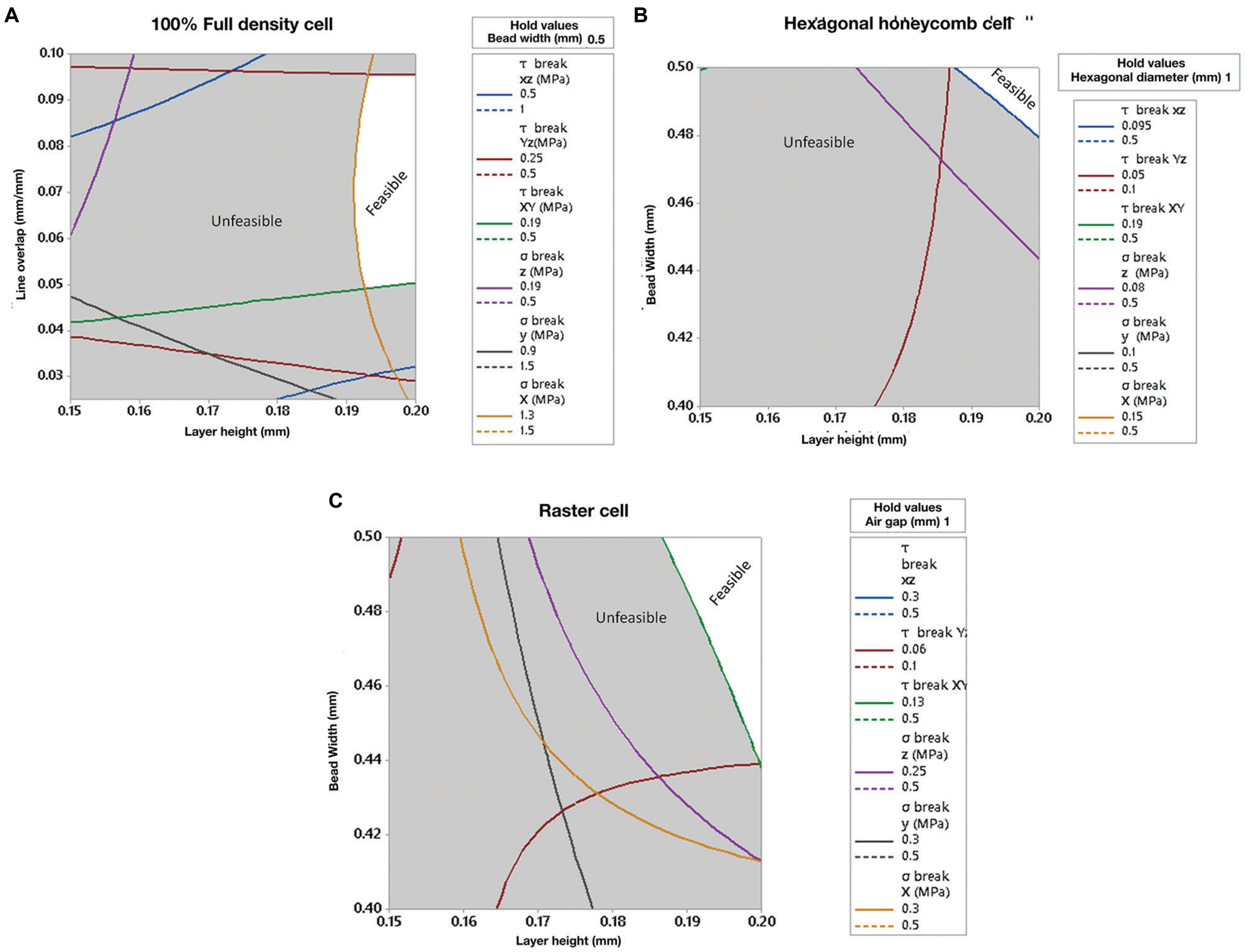


Figure 8. Overlap contour diagrams illustrating maximum mechanical strength as a function of (A) filament overlap, layer height, and filament width; (B) hexagon diameter, layer height, and filament width; and (C) air gap, layer height, and filament width.

object while increasing the contact area between layers. Conversely, an increase in layer height was found to enhance mechanical strength across all the studied areas. Similar findings were observed in raster cells, where larger fibers (with wider bead width and higher layer height) resulted in a more homogeneous material compared to smaller fibers (with narrower bead width and lower layer height).

In Figure 8, the overlap contour diagram indicates that the maximum mechanical strength is obtained in the high levels of layer height and bead width combined with a low hexagon diameter. Conversely, the lowest mechanical strength was observed in specimens fabricated with thin layers, small filaments, and large infill hexagons.

We also identified the linear orthotropic compliance matrix for hexagonal cells, as shown in Equation III. In this model, the yz and xz shear coefficients depend on hexagon diameter and layer height, while the xy coefficient depends on filament diameter and the interaction between hexagon diameter and filament diameter.

$$[C]=\begin{bmatrix} \begin{pmatrix}+0.2816\\-0.195\cdot w\end{pmatrix} & \begin{pmatrix}+0.069\\-0.0279\cdot d\\-0.1166\cdot w\end{pmatrix} & \begin{pmatrix}+0.0695\\-0.0594\cdot w\end{pmatrix} & 0 & 0 & 0 \\ \begin{pmatrix}+0.052\\+0.02884\cdot d\\-0.1152\cdot w\\+0.1305\cdot h\end{pmatrix} & \begin{pmatrix}+0.5213\\-0.1907\cdot d\\-0.818\cdot w\\+0.2244\cdot h\\+0.4206\cdot w\cdot d\end{pmatrix} & \begin{pmatrix}+0.1681\\+0.0699\cdot d\\-0.2634\cdot w\\+0.1368\cdot w\cdot d\end{pmatrix} & 0 & 0 & 0 \\ \begin{pmatrix}+0.513\\+0.02688\cdot d\\-1.135\cdot w\\-2.58\cdot h\\+6.26\cdot w\cdot h\end{pmatrix} & \begin{pmatrix}-0.271\\-0.1740\cdot d\\+1.301\cdot h\end{pmatrix} & \begin{pmatrix}+0.923\\-1.91\cdot w\\-4.38\cdot h\\+12.03\cdot w\cdot h\end{pmatrix} & 0 & 0 & 0 \\ 0 & 0 & 0 & \begin{pmatrix}-0.0531\\-0.03435\cdot d\\+0.369\cdot h\end{pmatrix} & 0 & 0 \\ 0 & 0 & 0 & 0 & \begin{pmatrix}+0.1237\\-0.0903\cdot d\\-0.149\cdot w\\+0.2558\cdot h\\+0.1622\cdot w\cdot d\end{pmatrix} & 0 \\ 0 & 0 & 0 & 0 & 0 & \begin{pmatrix}-0.01584\\-0.01557\cdot d\\+0.1466\cdot h\\-0.523\cdot h\cdot d\end{pmatrix} \end{bmatrix} \quad \text{(III)}$$

The typical coefficients were largely influenced by the diameters of the hexagon and the filament, with the layer height impacting the Poisson ratios and strength in the z direction.

The final cell type examined was the grid cell. In this cell type, the infill filaments are completely separated by air gaps, with their orientation shifts by 90° in each successive layer.

The air gap was identified as the control factor most detrimental to overall mechanical strength, while layer height was found to improve mechanical strength in all aspects except for the xz shear break, as presented in Figure 7. Importantly, bead width was also observed to increase the mechanical strength in all dimensions, supporting the hypothesis that objects fabricated with larger bead filaments are tougher than small bead filaments.

Figure 8 illustrates that small air gaps and large filaments strengthen the object when thicker layers are used. It also noted that bead width is the least important parameter in this analysis, as a wide range of values (0.44 – 0.5 mm) results in a similar effect on mechanical strength.

For the simplified numerical model of grid cells as a function of control parameters, Equation IV presents the regression of the linear orthotropic compliance matrix.

$$[C]=\begin{bmatrix} \begin{pmatrix} +0.869 \\ -0.339\cdot Hd \\ -1.646\cdot Wd \\ +0.741\cdot Hd\cdot Wd \end{pmatrix} & \begin{pmatrix} +0.0923 \\ -0.0429\cdot Hd \\ -0.143\cdot Wd \\ +0.0903\cdot Hd\cdot Wd \end{pmatrix} & \begin{pmatrix} +0.0402 \\ +0.02786\cdot Hd \\ -0.103\cdot Wd \end{pmatrix} & 0 & 0 & 0 \\ \begin{pmatrix} +0.0536 \\ -0.216\cdot Hd \\ -1.036\cdot Wd \\ +0.547\cdot Hd\cdot Wd \end{pmatrix} & \begin{pmatrix} +0.0584 \\ -0.0289\cdot Hd \\ -0.1139\cdot Wd \\ +0.0727\cdot Hd\cdot Wd \end{pmatrix} & \begin{pmatrix} -0.1616 \\ +0.06676\cdot Hd \\ +0.1408\cdot Wd \\ +0.0297\cdot h \end{pmatrix} & 0 & 0 & 0 \\ \begin{pmatrix} -0.1616 \\ +0.06676\cdot Hd \\ +0.1408\cdot Wd \\ +0.0297\cdot h \end{pmatrix} & \begin{pmatrix} -0.008 \\ -0.00323\cdot Hd \\ +0.372\cdot h \\ -0.265\cdot Wd \\ +0.263\cdot Hd\cdot Wd \end{pmatrix} & \begin{pmatrix} -0.2792 \\ +0.0911\cdot Hd \\ +0.352\cdot Wd \\ +0.528\cdot h \end{pmatrix} & 0 & 0 & 0 \\ 0 & 0 & 0 & \begin{pmatrix} -0.278 \\ +0.1616\cdot Hd \\ +1.195\cdot h \end{pmatrix} & 0 & 0 \\ 0 & 0 & 0 & 0 & \begin{pmatrix} -0.278 \\ +0.1616\cdot Hd \\ +1.195\cdot h \end{pmatrix} & 0 \\ 0 & 0 & 0 & 0 & 0 & \begin{pmatrix} +0.239 \\ -0.0642\cdot Hd \\ -0.552\cdot Wd \\ +0.237\cdot Hd\cdot Wd \end{pmatrix} \end{bmatrix} \tag{IV}$$

In this model, almost all normal coefficients were found to depend on air gap, filament diameter and layer height. In contrast, the normal coefficients in the x direction were primarily influenced by the air gap.

In this study, we also identified behavior patterns as a function of the type of anisotropy cell. Figure 9 indicates the average strength and stiffness of the anisotropic cells analyzed. Among the cell types, raster cells exhibited the highest capacity to withstand stress compared to grid and hexagonal cells. Conversely, hexagonal cells demonstrated higher average stiffness than raster and grid cells, although with a significantly larger standard deviation compared to the other cell types.

It is crucial to note that hexagonal and grid cells correspond to objects with very low density, while raster cells

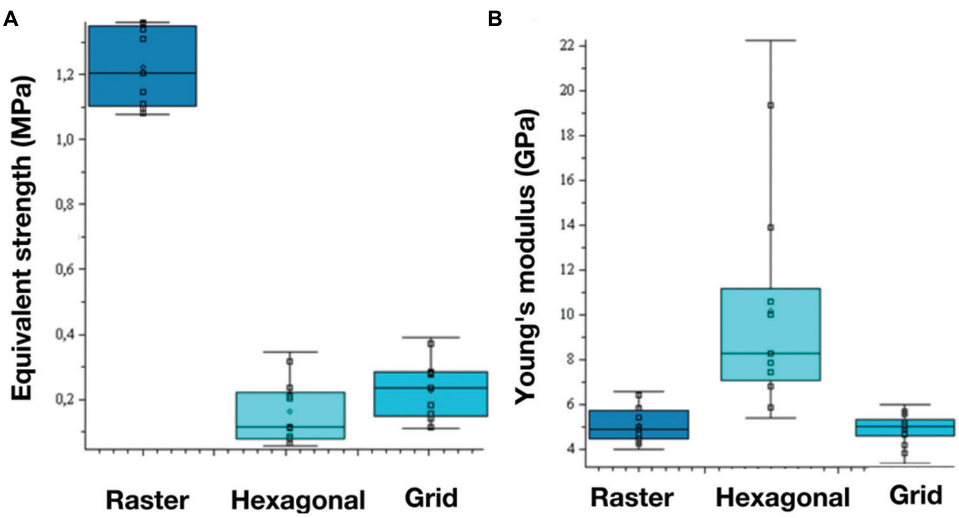


Figure 9. Comparison of (A) mean normal break equivalent stress and (B) mean normal Young's modulus for different types of anisotropic cell: raster cell, hexagonal cell, grid cell.

usually have 100% material density. By considering the type of cell and its stress levels, object topology can be optimized based on the anisotropic cell type and fabrication parameters.

Statistical analysis was performed using *t*-tests and F-tests to determine differences in mean and variance. The results indicated that hexagonal and grid cells statistically have the same mean and variance in strength, while raster and grid cells show statistically identical mean and variance for Young's modulus.

In the case study, we analyzed the specimen using a detailed finite element method and compared it with a simplified finite element method featuring linear orthotropic stiffness cells. In addition, the physical specimen was evaluated to assess the accuracy of the numerical models.

In Figure 10, the equivalent stress-deformation diagrams of the two numerical models are presented. A slight behavior difference is observed, with the

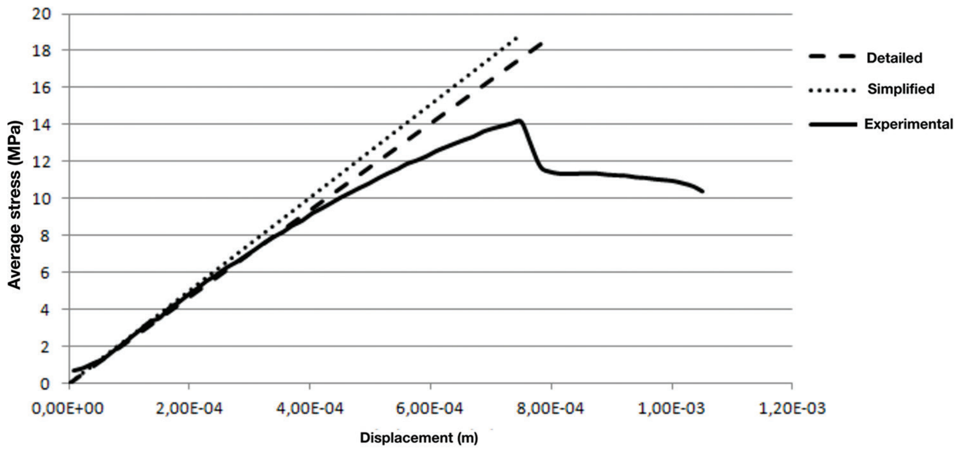
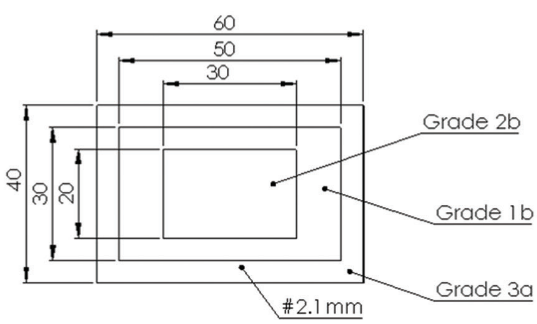


Figure 10. Comparison of detailed model total deformation

A

		Grade 1		Grade 2		Grade 3	
		a	b	a	b	a	b
w	0.5mm	x	x	x	x	x	x
	0.4mm						
h	0.15mm	x	x	x	x	x	x
	0.2mm						
airgap	1mm	x					
	2mm		x				
hex	1mm			x			
	2mm				x		
overlap	0%					x	
	15%						x
orientation	0°	x		x	x	x	
	90°		x				x



B

	Grade 1		Grade 2		Grade 3	
	a	b	a	b	a	b
1/Ex	0.2	0.17	0.08	0.13	0.23	0.21
1/Ey	0.2	0.18	0.09	0.12	0.21	0.19
1/Ez	0.19	0.21	0.04	0.16	0.15	0.16
1/Txy	0.047	0.067	0.04	0.34	0.27	0.38
1/Txz	0.074	0.067	0.03	0.27	0.25	0.26
1/Tyz	0.02	0.021	0.02	0.08	0.04	0.25

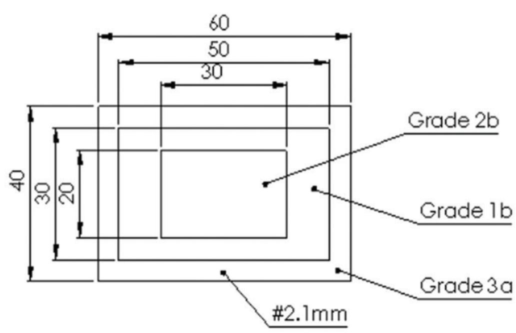


Figure 11. Proposal of engineering specifications for technical drawing where: (A) The technical specification defines process parameter per area; (B) The technical specification defines anisotropic strength per area. Notes: w: Filament width; h: Layer height; Ex: Normal stiffness coefficient in x direction; Ey: Stiffness coefficient in y direction; Ez: Stiffness coefficient in z direction; Xy; Angle between x and y; Xz; Angle between x and z; Txz: Shear stiffness coefficient in xz direction; Tyx: Shear stiffness coefficient in yx direction.

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simplified model displaying an average Young's modulus approximately 1 GPa higher than the detailed model; despite this discrepancy, the difference remains minimal.

The deformation and maximum internal stress of the detailed model were found to be higher than those of the simplified model under the same load conditions.

Despite minor differences between the models, their equivalence can be demonstrated, with the simplified model offering a significant reduction in computational time – from about 1 h for the detailed model to just 15 s. In addition, this study examined the use of linear orthotropic stiffness cells based on 3D printing process parameters through both experimental and theoretical approaches.

As a result, a simplified model was developed, and comparisons among the detailed, simplified, and experimental models showed a strong correlation between them. This advancement enables the design of complex objects with various anisotropic internal structures and the identification of process parameters corresponding to these cell properties. This leads to more reliable design specifications compared to current techniques, ensuring an accurate representation of the mechanical behavior of 3D-printed objects.

Thus, the simplified model can be used for designing such objects, reducing computational costs across various environments, including computer-aided design, computer-aided engineering, slicers, and computer-aided manufacturing.

The basic design specifications can be divided into two categories: process-based and engineering-based.

As illustrated in Figure 11A, the number of parameters and the degree of anisotropic strategies can be effectively specified for objects with simple material behavior. However, objects requiring more complex levels of anisotropy may lead to specifications that are harder to interpret and visualize.

This approach integrates the process directly into the design, ensuring that the final product aligns with desired outcomes. Consequently, defining process parameters becomes an integral part of design activities. This underscores the importance of product engineers, designers, and engineering designers having a thorough understanding of the manufacturing process to achieve optimal results.

Another sort of specification is based on engineering parameters, where the basic orthotropic coefficients define the material grades, as presented in Figure 11B. In this case, the process parameters are defined during manufacturing planning using a reference table.

This approach empowers manufacturing engineers to define and optimize process parameters while maintaining alignment with engineering specifications. A notable advantage of this method is that designers, engineering designers, and product designers do not need to have in-depth knowledge of the manufacturing process.

4. Conclusion

In summary, this research demonstrated the anisotropic behavior of FFF specimens through both computational simulations and experimental tests, successfully validating numerical models against experimental data. The study identified key and secondary factors influencing anisotropic cell behavior, including layer height, filament diameter, hexagonal infill diameter, air gap, and line overlap.

It was observed that raster cells exhibit greater resistance compared to hexagonal and grid cells, primarily due to the lower density of hexagonal and grid cells. However, hexagonal cells were found to have a higher average Young's modulus compared to grid and raster cells. Variables such as layer height (for raster cells), hexagon diameter (for hexagonal cells), and air gap (for grid cells) were identified as having significant effects on equivalent break stress and elasticity modulus. In addition, the combination of bead width and layer height suggests that larger beads produced stronger objects compared to smaller bead filaments.

The study determined the coefficients for linear orthotropic compliance matrices, leading to a simplified numerical model with low computational costs. This research represents an initial framework for integrating anisotropy characteristics into design specifications despite manufacturing variations like infill density and layer height.

Two design specification methods were proposed to standardize the mechanical behavior of both complex and simple 3D-printed objects. Nonetheless, many challenges remain, and further research is needed to refine the integration of anisotropy in design specification based on process parameters.

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Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: All authors
Methodology: All authors
Investigation: All authors
Writing – original draft: All authors
Writing – review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Data are available from the corresponding author upon reasonable request.

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ARTICLE

Balancing innovation and trust: Assessing artificial intelligence's role in medical history taking and physician perspectives on patient care

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Abstract

This study explores the potential of artificial intelligence (AI) in medical history taking (anamnesis) and assesses its acceptance using technology acceptance models. Through nine expert interviews with physicians from diverse medical backgrounds, the study aims to understand concerns and anticipated benefits of AI in the doctor–patient relationship. To demonstrate AI's applications, digital anamnesis surveys were conducted with two actual patients, and the resulting data were interpreted by AI and reviewed by physicians. Findings indicate that physicians view AI as potentially beneficial, expecting that AI can facilitate improvements in care quality, efficiency, and time savings. Despite initial concerns about AI's ability to address individual patient needs and its impact on the doctor–patient relationship, there is significant interest in integrating AI tools into daily practice. Key issues include patient constitution, the effort-to-benefit ratio, and potential risks to patient trust. The study identifies six areas for further research: Economic impact and cost-benefit analysis, patient acceptance and trust, stress reduction and job satisfaction, effects on doctor–patient relationships, development of verification mechanisms, and ethical and legal considerations. These findings underscore the complexities of AI integration in health care, emphasizing the need to address concerns about patient individuality, data privacy, and interpersonal relationships while harnessing AI's potential.

Keywords: AI-enhanced anamnesis systems; AI technology acceptance; AI quality assumptions; Idana; AI in medical history taking

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1. Introduction

Recent advancements in artificial intelligence (AI) have sparked considerable interest in its application across various sectors,[1] including health care.[2] AI's potential to enhance medical history taking is particularly promising, a fundamental aspect of patient care that influences diagnosis, treatment, and overall health-care outcomes. By automating and streamlining the process, AI can significantly improve efficiency and precision in medical practice.[3]

The application of AI in medical anamnesis has been gaining momentum, particularly in fields such as anesthesiology and surgery. AI has demonstrated significant potential in enhancing various medical processes, from patient record-keeping to real-time monitoring and decision-making. For instance, AI-supported systems such as anesthesia information management systems facilitate automated record-keeping, predictive analytics, and patient monitoring, which have proven to be vital in improving anesthesia management and patient safety.[4] Furthermore, AI applications in anesthesiology have expanded to include event prediction, ultrasound guidance, pain management, and operating room logistics, underscoring its multifaceted role in modern.[5]

AI's integration into surgical practices has also been transformative, particularly in pre-operative planning, intraoperative guidance, and the use of surgical robots. AI technologies have been instrumental in improving the accuracy and efficiency of surgical procedures through enhanced imaging, navigation, and real-time decision support systems.[6] In addition, AI-driven intraoperative decision support systems aim to augment the information available to surgeons, accelerate pathology analysis, and recommend surgical steps, thus potentially improving patient outcomes.[7]

Beyond anesthesiology and surgery, AI has found applications in various medical disciplines, including dentistry and brain care. In dentistry, AI has enhanced diagnostic accuracy and treatment planning through advanced data analysis and visualization techniques.[8] In brain care, AI has been utilized for diagnosis, surgical planning, and post-operative assessment, showcasing its ability to handle complex medical data and provide meaningful insights for clinical decision-making.[9] These advancements highlight AI's potential to revolutionize medical practices across various specialties.

Despite the promising applications, several challenges hinder the widespread adoption of AI in medical anamnesis. Data quality and quantity, technical limitations, and ethical and legal concerns are significant obstacles that need to be addressed to ensure the reliable and secure implementation of AI systems.[10] Overcoming these barriers requires the development of robust guidelines for ethical AI use, improvement in AI system reliability, and certification of health data precision and security. As AI continues to evolve, future research should focus on expanding its applications, enhancing data security, and integrating AI into medical education and training to fully realize its potential in medical anamnesis.[11]

In the realm of AI-driven medical history-taking and patient dialogue, significant advancements have been made, yet there remain gaps that warrant further exploration. AI systems such as dialogue-contextualized re-ranking models have been developed to enhance medical history-taking by addressing training-inference gaps and improving question relevance during patient interactions.[12] In addition, virtual standardized patients utilizing AI for natural language understanding and rule-based dialog management have shown promise in medical education, enabling students to practice history-taking with high conversational fidelity.[13]

Furthermore, the feasibility and acceptability of conversational AI systems for medical interviewing have been positively received by patients, suggesting that these tools can aid clinicians in understanding patient health and identifying risk factors.[14] However, comprehensive knowledge-grounded dialogue systems for medical conversations are still in the early stages, and there is a need for more robust systems capable of accurately extracting and utilizing heterogeneous medical information.[15]

The research analyzed reflects medical history only to a limited extent. The main focus of the researched use of AI is on technical analysis,[16] e.g., image interpretation or support in surgical matters.

Based on our literature, we identified a significant research gap in the widespread acceptance and practical implementation of AI in medical anamnesis. Studies show that while there is optimism about AI's role in medicine, there are concerns about its reliability and integration into clinical practice.[17] Physicians and medical students generally have positive attitudes toward AI but lack practical experience and knowledge, highlighting the need for comprehensive AI education in medical curricula. Moreover, there is a noticeable reluctance among health-care providers to trust AI systems over human judgment, underscoring the need for further research into improving AI's reliability and addressing ethical and regulatory concerns.[18] Future research should focus on bridging these gaps to enhance AI's integration into clinical workflows, ensuring both clinicians and patients benefit from AI advancements in medical anamnesis.

However, to realize the benefits of using AI in the clinical environment, it is also necessary to consider the acceptance of the technology by the users. Can existing technology acceptance models be used to successfully evaluate AI applications in medical history, i.e., in the close doctor–patient relationship? (Research question 1, RQ1).

It is also important to examine the deeper attitudes of users. What concerns do physicians have about using AI to support part of the medical history taking? (RQ2). We can also look at what benefits users expect from AI in medical history taking (RQ3). The combined answer to RQ2 and RQ3 leads to the expected intention to use and therefore to RQ4. The study design and the research questions are summarized in Figure 1.

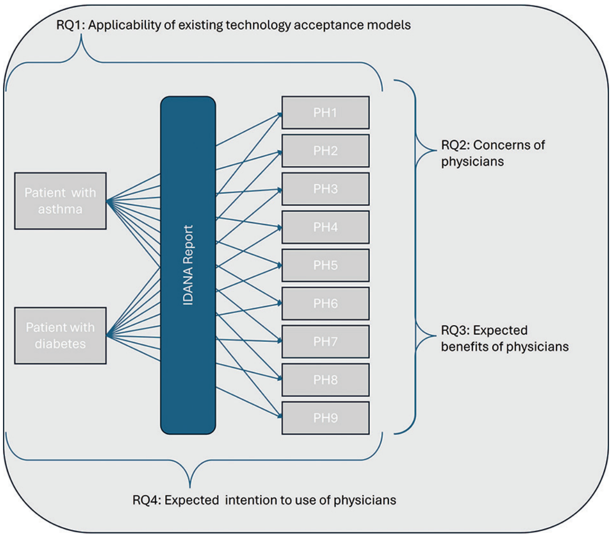

Figure 1. Study design
Abbreviation: PH: Physician.

This study focuses on exploring how AI can transform medical history taking, emphasizing its capacity to alleviate health-care professionals' workload while potentially improving patient outcomes. History taking and clinical examination are key functions for physicians in identifying patients' health problems, and accurate assessment and referral are critical for targeted and cost-saving diagnosis and therapy.[19] The need to support physicians in their patient processes is not new,[20] and auto-anamnesis concepts have been explored since the 1970s.[21] However, with the potential of AI, a big step forward could be possible. Understanding the acceptance of AI technologies among health-care providers is crucial for successful integration into clinical settings.[22] This investigation aims to evaluate existing technology acceptance models in the context of AI applications within the doctor–patient relationship, uncovering both the opportunities and challenges involved.

Furthermore, the study examines physicians' concerns regarding the adoption of AI in medical history taking and explores their expectations regarding the benefits AI can offer in this domain. By addressing these research questions, this research seeks to contribute to the growing body of AI knowledge in health care, providing insights that can inform future implementations and policies aimed at optimizing patient care through technological innovation.

The study provides valuable insights into the reception of AI tools among medical professionals, potential benefits and challenges, and crucial areas for future research. The main contributions include:

1. Demonstrating positive reception among medical professionals
2. Identifying potential efficiency and quality improvements
3. Highlighting integration challenges
4. Outlining key areas for future research
5. Providing insights into AI adoption in health care
6. Acknowledging limitations and research gaps
7. Emphasizing the need for interdisciplinary research
8. Offering practical implications for AI tool development and implementation.

These findings contribute to the broader understanding of AI's role in health-care explicitly in medical history taking and provide a foundation for further research and development in this field.

2. Methods

2.1. Research strategy

A qualitative methodology was employed to address the research questions. We conducted interviews with physicians who are prospective users of an AI-enhanced medical history system. To ensure a realistic simulation, two hypothetical patients with chronic conditions – namely asthma and diabetes – were asked to complete a digital medical history form. These particular diseases were selected due to their significant impact on treatment across a wide spectrum of medical specialties.

To demonstrate the specific capabilities and applications of AI in medical history taking, utilization of general medical history forms was eschewed in favor of utilizing the technology developed by Idana. Idana, a start-up company that has been providing digital anamnesis tools for various medical disciplines since 2019, was selected. Idana's anamnesis forms have documented over one million patient records and have analyzed this data using AI. Given their 5 years of experience in digital anamnesis collection and the highly positive feedback from medical professionals such as cardiologists in Kardiologen Rostock[23] and the National Association of Statutory Health Insurance Physicians,[24] the Idana tool was chosen to create the two sample questionnaires.

Patients interact with Idana through pre-selected medical history forms, accessible through a quick response code. They can anonymously complete the medical history form and submit it to the app's system. The AI then generates a summary of the submitted information, highlighting relevant data (Appendix A). We used the two anonymized patient data to give the doctors interviewed the most realistic possible access to the interview situation in the sense of a vignette.[25,26]

In addition to personal contact details, the questionnaire contains the initial reason for the doctor's visit and the following additional sections: Previous illnesses, family history, allergies, medication, social environment, stimulants, bodily functions, stress level, and possible expectations and fears. The questionnaire contains a total of around 80 questions. Each answer can be marked with a yellow exclamation mark by the included AI, thereby generating a corresponding support signal for the attending physician. The complete anamnesis questionnaire that was used as a template for the interviews can be found in Appendix A.

Throughout this process, patient anonymity is preserved, and stringent measures are taken to ensure the confidentiality of sensitive information.

Semi-structured, guideline-based, problem-centered expert interviews were conducted between February 20, 2024, and March 17, 2024. Initially, a guideline was developed, which served as the foundation for the interviews. This guideline was systematically formulated by developing key questions that were subsequently transformed into specific interview questions. During the creation of the interview guidelines, careful consideration was given to various dimensions of the topic to ensure a holistic approach. This included questions addressing the potential consequences for medical practice, as well as an exploration of concerns, opportunities, hopes, and the general acceptance of AI in medical history taken by the medical profession.

Before the interviews, participants were verbally informed about the research topic and the interview process, and their consent was obtained. Before commencing the interviews, the physicians were provided with a demonstration of Idana's functions and results, which served as a foundation for the subsequent discussions. The combination of these two methods – interviews with physicians and the use of the Idana app for patient surveys – provides a comprehensive basis for elucidating the opportunities and challenges associated with integrating AI into medical history taking.

2.2. Methodology

For this qualitative study, a sample of nine physicians from various specialties was recruited. The selection was purposive to capture a diversity of experiences and opinions from doctors in different fields and positions. The two medical conditions included in our analysis, asthma, and diabetes, can influence the medical history in different medical fields, even if the respective specialties do not treat the specific disease. The combination of doctors from different medical professions, therefore makes a valuable contribution to this study. Factors such as age, gender, professional experience, and area of practice were considered to ensure a broad perspective on data collection (Appendix B).

Small sample sizes in qualitative research allow for a more detailed and nuanced exploration of individual experiences and perspectives.[27] In qualitative research, sample sizes are often determined by the point of theoretical saturation – the point at which no new information or themes are observed in the data. This can often be achieved with smaller samples.[28]

All interviews took place in Upper Bavaria in the spring of 2024. The interviews were conducted face-to-face, with the choice of location adapted to the participant's preferences, to create a relaxed interview atmosphere that allowed the experts to speak freely and openly about their experiences, opinions, and concerns regarding the use of AI in medical practice. The doctors gave their initial verbal consent to participate when first asked.

The study participants represented a wide age range, from 33 to 59 years, with an average age of 47 years. The specialties included internal medicine, cardiology, otolaryngology (including specialized ear, nose, and throat surgery and facial plastic surgery), gastroenterology, conservative orthopedics, orthopedics, rehabilitative and physical medicine, as well as neurology and psychiatry. One physician practiced general medicine. The participants held various positions in their careers, such as specialist, senior physician, and assistant physician. They worked in both clinical and outpatient settings, including group practices and shared practices. The sample included physicians working in clinics (five physicians) and private practices (four physicians). Regarding their experience with AI, five of the participants reported having no prior knowledge, while four had experience with AI tools. This similar separation path was also employed by Chaddad *et al*.,[29] indicating this selection is well-experienced and suitable for this study.

The study's diverse sample, covering a wide age range (33 – 59 years), multiple specialties, various career stages, and different practice settings (clinical and outpatient), ensures comprehensive insights. In addition, the inclusion of both novice and experienced AI users further mitigates selection bias, providing a balanced view of AI's impact on health care.

The transcription of the interview data employed the semantic-content transcription method by Dresing and Pehl.[30] This method emphasizes the substantive content of the conversations by omitting detailed pronunciation information, thus facilitating quick access to the conversation content and enhancing readability compared to the gesprächsanalytisches transkriptionssystem transcription method. The clear transcription rules used in this approach contribute not only to scientific reproducibility but also help maintain focus during both transcription and subsequent reading. Kuckartz supports this view, noting that deliberately simple and quickly learnable transcription rules smooth out the language and emphasize the semantic content of the utterances.[31] By applying this transcription method, the data collected were precisely captured and subsequently analyzed efficiently. The structured transcription process following Dresing and Pehl's guidelines enabled systematic analysis of the interview content, significantly contributing to the generation of meaningful results. The transcription adhered to the following rules outlined by Dresing and Pehl in "Praxisbuch Interview, Transkription, and Analyse."

Data analysis was conducted using qualitative content analysis according to Kuckartz, utilizing the software MAXQDA. Initially, the transcribed interviews were uploaded to MAXQDA to commence the analysis. The qualitative content analysis followed the steps defined by Kuckartz.

The coding was aligned to the technology usage inventory (TUI) by Kothgassner *et al.*[32] The TUI developed by Kothgassner *et al.*[32] is a model designed to measure technology acceptance and usage behavior. The TUI consists of several dimensions that evaluate different aspects of technology acceptance:

- Accessibility (ZUG)
- Immersion (IMM)
- Usefulness (NUT)
- Ease of use (BEN)
- Interest (INT)
- Curiosity (NEU)
- Technology anxiety (ANG)
- Technology skepticism (SKE).

These dimensions collectively provide a comprehensive understanding of technology acceptance and usage behavior, taking into account not only the functional and practical aspects of the technology but also the psychological[33] and social factors that influence user behavior and are therefore more aligned with our research focus than the other well-known models.[34]

3. Results

The analysis of the interview data revealed that physicians' statements about their general acceptance of technology corresponded to the categories of the TUI.

Figure 2 shows that the factors of usefulness, interest, and usability, which have a positive impact on technology acceptance, were mentioned in almost all interviews, with no significant difference between physicians with and without previous experience of AI. Accessibility and curiosity, which also have positive effects, were mentioned less frequently. We understand that this might come from the fact that many interviewees (seven out of nine without prior knowledge concerning AI) had no prior experience with AI tools in medical history taking.

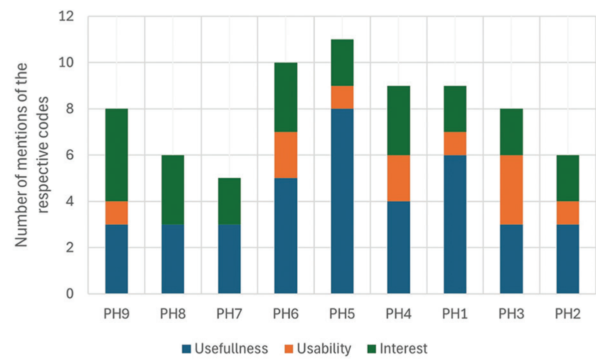

Figure 2. Code trends technology acceptance
Abbreviation: PH: Physician.

The majority of interviewees expressed skepticism, often due to a lack of understanding of the practical application and spatial implementation of AI in their practices:

> *"I don't have any idea how it would work in practice. I also don't have an idea how it should work spatially."* (I04, L152ff).

Four doctors expressed a certain fear of technology. Despite this, all interviewees were very interested in the functions of AI tools. Although curiosity was only touched upon briefly, it was evident during the interviews, particularly while discussing and inspecting the Idana tool. In questions 15 and 16, interpersonal curiosity and interest were particularly evident, with all physicians expressing their willingness to accept technological support regarding their intention to use the tool:

> *"Well, I'm basically open to new technologies. Including AI. And I can well imagine trying something new."* (I07 – L84 – 85)

These findings suggest that the TUI can successfully evaluate AI applications in medical history taking by addressing factors such as perceived usefulness, ease of use, and interest. However, the models need to consider the practical challenges and skepticism that health-care professionals might have toward AI.[35]

The TUI has proven itself in this qualitative study as a model for evaluating the technology acceptance of completely new application possibilities. The expansion of the constructs characterized by usefulness to include psychological constructs such as curiosity and anxiety has proven successful in this context (RQ1).

From the TUI, the construct anxiety can be used in combination with the answers of the interviewees to shed light on the concerns of potential users and thus answer RQ2.

The findings of this research highlight several significant concerns expressed by physicians regarding the integration of AI in medical history taking. A major apprehension is that AI tools may not adequately address the individual needs and health conditions of patients, potentially compromising the quality of care.

In addition, physicians emphasize the importance of the doctor–patient relationship, fearing that AI technologies could undermine the personal contact and interpersonal connections that are crucial in medical practice. Concerns were also raised about data protection, the potential for errors, and patient uncertainty. These insights reflect the broader apprehensions among medical professionals about the impact of AI on the nuances and complexities of patient care.

> *"However, I still see great dangers if there is not enough demand and the more a system is used for treatment, the more a system is used, the greater the source of error. But the doctor himself is of course also a source of error."* (I02, L98 – 99)

These findings underscore the complexity and multifaceted nature of the challenges associated with implementing AI in medical practice, emphasizing the need for careful consideration of the potential risks and benefits in terms of patient care and the doctor–patient relationship.

RQ3 focuses on the benefits of using AI in medical history taking. Analysis of the interview data regarding the potential benefits of AI in medical history taking reveals a wide range of positive aspects highlighted by the physicians surveyed. The data collected suggests that AI-based approaches can make a significant contribution to improving various aspects of medical practice. Most importantly, physicians unanimously agreed that AI makes their work easier. All respondents saw great potential for AI to support their work.

> *"I think, above all, it saves us time and allows patients to fill out their medical history at home. And then we have already filled it out, the file, the documents are prepared and then we can also ask the patients specific questions."* (I06, L. 47 – 50)

In addition, a large majority of respondents expressed the expectation that the use of AI would lead to an improvement in the quality of care. In particular, the potential reduction of physician errors was cited as a factor in improving the quality of care. Increased efficiency and associated time savings were also cited by a significant number of respondents as potential benefits of AI in medical history taking. In addition, it was highlighted that the use of AI could increase patient trust and satisfaction, which could lead to an overall more positive patient experience and increased trust in medical care. Detection of health risks and the ability to better target medical history taking were also cited as potential benefits of AI in medical history taking.

> *"Yes, well, I just said a bit earlier (laughing). I think it's good that the patient has the feeling that they can now do something themselves. They're not just sitting down and made to wait. Somehow, they can become active themselves."* (I03 – L77-79)

This illustrates the potential of AI-based approaches to identify health risks at an early stage and to better tailor the medical history to the individual needs of the patient. Three of the respondents also saw potential in the standardization and structuring of data, which could be ensured by an AI system.

However, this does not lead to the integration of AI into the daily work of the physicians surveyed. Intention to use is a construct that needs to be evaluated. The use of a technology acceptance model in combination with a reflection of the use in a specific application area can explain the intention to use.[36]

To shed light on RQ4, we analyzed the codes that we had obtained through the interviews. Based on Güsken *et al.*'s research[36] on the "factors influencing the intention of caregivers to use digital technologies in outpatient care," we organized the analysis into two main segments – technology acceptance and actual situation (here anamnesis).

The focus on technology acceptance was answered with RQ1. Therefore, we focused on the medical history and physician responses. The key factors we identified that need to be addressed to impact usage intention positively are shown in Figure 3. The figure shows the frequency of nomination of relevant codes within the dimension of the analyzed factors.

The intention to use AI in medical history taking is influenced by a combination of perceived benefits and concerns, encapsulated in the factors of time, stress level management, adaptation to the area of application, doctor–patient relationship, and system functions as shown in Figure 3.

AI promises significant time savings by streamlining the anamnesis process. Physicians reported that AI could shorten the time needed for data collection, allowing them to focus more on patient care and complex clinical tasks. This efficiency gain is a compelling reason for adopting AI in medical settings.

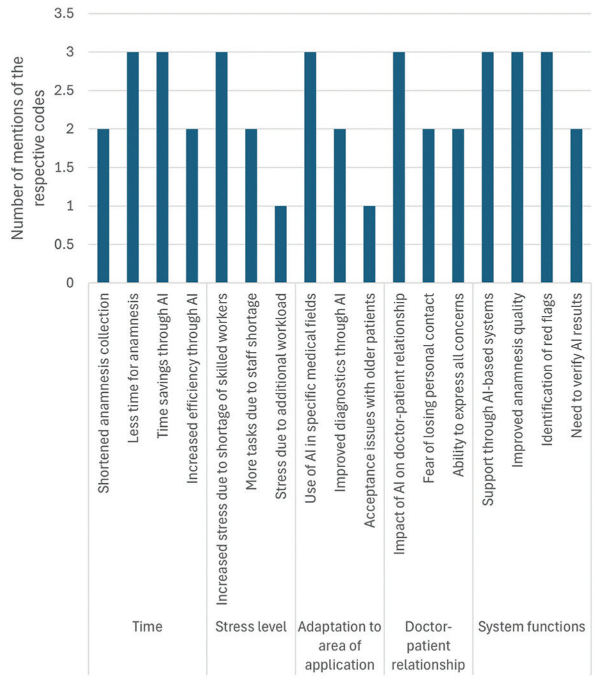

Figure 3. Frequencies of codes building the factors influencing the intention to use

The analysis highlighted that AI could alleviate stress by reducing the workload on medical staff. By automating routine tasks, AI helps manage the stress associated with staff shortages and increasing administrative duties, making it a valuable tool for improving workplace conditions.

Physicians acknowledged AI's potential to enhance diagnostic accuracy and efficiency in specific medical fields. The ability of AI to adapt to different specialties and provide precise support was seen as a significant benefit, driving its intended use across various medical disciplines.

Concerns were raised about AI potentially diminishing personal interactions between doctors and patients. However, many physicians believe that AI can help enhance these interactions by handling preliminary data collection, thus allowing more quality time for direct patient engagement.

AI's capability to support medical professionals through advanced system functions was another factor influencing its intended use. AI can improve the quality of anamnesis, identify red flags, and ensure comprehensive data collection. However, the need for robust verification mechanisms to ensure the reliability of AI-generated information remains a critical consideration.

The combined insights from these factors reveal a cautiously optimistic intention to use AI in medical anamnesis. Physicians recognize the substantial benefits of efficiency, stress reduction, and enhanced diagnostic accuracy, which strongly motivates the adoption of AI. Nevertheless, addressing concerns about the doctor–patient relationship and ensuring the reliability of AI systems are crucial for its successful implementation. Ultimately, the intention to use AI in medical history taking is driven by its potential to significantly improve patient care while managing the inherent challenges associated with its adoption.

The doctors surveyed had very different personal data, be it the specialist discipline, the amount of professional experience, or the employment relationship. Nevertheless, the interview statements were characterized by a surprising similarity.

A similarity matrix was created to illustrate the similarity of the interview data.[37] This was created taking into account the variables of age, workplace/position, and experience with AI based on the occurrence of the codes. The "simple match" was selected as the calculation variant, which evaluates both the presence and absence of codes as a match. This variant was chosen because all codes were assigned in the majority of the documents and the absence of codes therefore does not play a dominant role compared to the presence of codes. The following results were found for the nine interviews:

The matrix in Table 1 illustrates the similarity of the respondents' answers, with 1.00 corresponding to 100% agreement and 0.00 corresponding to 0% agreement. The data indicates that the interviews of respondents B09 and B05 exhibit a high degree of similarity in terms of both coding and variables, with a value of 0.88. Conversely, the interviews of respondents B02 and B06 demonstrate the least similarity, with a value of 0.42. The overall average similarity of the interviews is 0.68.

4. Discussion and prepositions for further research

The analysis of interviews with medical professionals reveals a generally positive reception toward AI-supported anamnesis, highlighting its potential to enhance efficiency and precision in patient care. All surveyed doctors expressed willingness to incorporate AI tools like Idana into their daily practice, citing time savings and improved treatment quality as primary advantages.

One respondent articulated this sentiment succinctly:

> *"I think, above all, it saves us time and allows patients to fill out their medical history at home. And then we have already filled it out, the file, the documents are prepared and then we can also ask the patients specific questions."* (I06, 47 – 50)

Table 1. Similarity matrix

Document name	PH 09	PH 08	PH 07	PH 06	PH 05	PH 04	PH 03	PH 02	PH 01
PH 09	1	0.73	0.61	0.79	0.88	0.73	0.48	0.58	0.67
PH 08	0.73	1	0.52	0.64	0.67	0.76	0.45	0.55	0.58
PH 07	0.61	0.52	1	0.58	0.73	0.7	0.64	0.61	0.58
PH 06	0.79	0.64	0.58	1	0.79	0.64	0.58	0.42	0.7
PH 05	0.88	0.67	0.73	0.79	1	0.79	0.61	0.58	0.73
PH 04	0.73	0.76	0.7	0.64	0.79	1	0.58	0.73	0.64
PH 03	0.48	0.45	0.64	0.58	0.61	0.58	1	0.67	0.7
PH 02	0.58	0.55	0.61	0.42	0.58	0.73	0.67	1	0.55
PH 01	0.67	0.58	0.58	0.7	0.73	0.64	0.7	0.55	1

Note: The shades of grey indicate the degree of similarity.
Abbreviation: PH: Physician.

This efficiency gain is further exemplified by another interviewee:

> *"I could imagine that it is impressive for patients if the doctor has a lot of information in a differentiated context right from the start and you can delve deep into their health problems during the consultation."* (I07, 59ff)

"Therefore, the ultimate question is: will health-care organizations successfully adopt AI?"[38] The present study at least gives clear indications that the doctors responsible are open to the use of AI and goes some way to answering the core question of Sezgin's 2023 study.[38]

However, the integration of AI in medical anamnesis is not without challenges. Concerns were raised regarding data protection, patient constitution, and potential impacts on the doctor–patient relationship. As one respondent noted:

> *"Well, if a kind of data protection could be guaranteed if the patients could simply reserve the right for the doctors to maintain confidentiality toward the insurance companies."* (I09, 87 – 89)

These findings, while insightful, are limited by the study's small sample size, self-selection of participants, and regional constraints. To address these limitations and further explore the potential of AI in health care, we propose several areas for future research:

The prepositions are aligned to our analytic model combining the elements of the TUI concept with the situative demands within the anamnesis situation.

(A). Economic impact and cost-benefit analysis (Technology acceptance: perceived usefulness)

Economic studies evaluating the cost-effectiveness of implementing AI in medical anamnesis are necessary. This research should consider both short-term and long-term financial impacts on health-care systems and individual practices.

> *"I have high hopes that patient care can be improved through AI support. Improvement can be achieved. I wonder whether this necessarily only has to be in terms of taking medical histories. I also see potential in administrative areas. When it comes to reducing bureaucracy, writing applications and paperwork and things like that. Documentation. To be honest, I have more hope there than with regard to taking medical histories."* (I07, 72 – 77)

The meta-study by Khanna *et al.*[39] shows that the combined evaluation of diagnostic and therapeutic models offers greater savings. The review of the literature on the economic impact of implementing AI in health-care shows clear evidence that the use of AI in health-care sectors such as ophthalmology, radiology, and disease screening has shown positive economic impacts. The area of medical history is not reflected as a single area of application.[40]

The economic challenges of using AI in the practices of registered doctors suggest an even greater challenge than can be expected in inpatient facilities with an existing IT support infrastructure. This is therefore an area where further research is needed.

(B). Patient acceptance and trust (Technology acceptance: Skepticism and technology anxiety)

Exploring patients' perceptions and acceptance of AI in medical anamnesis is vital. Studies should examine how patients feel about interacting with AI systems and whether this influences their trust in the medical care they receive.

> *"And I think (.) I think it also increases patient satisfaction because they have the feeling that, firstly, they can deal with something, they are taken*

seriously, they can enter everything and it's not a doctor who somehow has a minute and then runs off again."(I3; 60 – 64)

As Esmaeilzadeh *et al.*[41] outlines, even though physicians and other health-care stakeholders are adopting AI to varying degrees, it is vital to understand patients' attitudes toward these different scenarios. However, there is currently limited insight into the risk perceptions associated with using AI for diagnosis and treatment in a clinical setting from the general public's perspective.

Technology acceptance and, above all, trust in the way AI works in medical history taking requires further consideration.

(C). Assessing stress reduction and job satisfaction (Situation-anamnesis: Time and stress level)

Quantitative studies are needed to measure the impact of AI on health-care professionals' stress levels and job satisfaction. This research can provide insights into how AI's role in reducing routine tasks influences overall workplace morale and mental health.

"Of course, I first have to read and evaluate what the AI then spits out. That also takes time." (I04, 60f)

Karal and Turan[42] are considering the use of AI in anamnesis as helpful to diagnose patients more accurately but their insights do not address stress reduction or job satisfaction.

(D). Evaluating the impact on doctor–patient relationships (Situation-anamnesis: Doctor–patient relationship)

Longitudinal studies should be conducted to assess how AI integration in anamnesis affects the quality and depth of doctor–patient interactions over time. This research should aim to identify strategies to mitigate any potential negative impacts on these crucial relationships.

"But I could also imagine that patients find that more of a hindrance to building a sustainable doctor–patient relationship. They attach more importance to starting slowly, slowly getting into conversation." (I07, 61 – 64)

Sauerbrei *et al.*[43] states in their literature review: "In the longer term, the debate is still open with regards to how human preferences for AI-led health care will evolve." The subject of the doctor–patient relationship under the influence of the use of AI has obviously not been finalized.

(E). Developing robust verification mechanisms (Situation –anamnesis: Adoption to area of application)

Future research should focus on creating and testing verification systems to ensure the accuracy and reliability of AI-generated anamnesis data. This includes exploring methods for integrating AI with existing medical record systems and establishing protocols for human oversight. The study of Chadadd points out: "More particularly, it is necessary for the actual XAI (explainable AI – the author) application to take into account users without the necessary AI training."[29]

"But in neurology in particular, we have patients who are not quite cognitively capable of operating, selecting and answering the questions. So I don't know to what extent that's really the case for us." (I09, 107ff)

(F). Ethical and legal considerations (Situation-anamnesis: System functions)

Research addressing the ethical and legal implications of using AI in medical history-taking is essential. This includes exploring issues related to data privacy, consent, and the responsibility of medical professionals in cases of AI errors.

"In the area of data protection, for example, there are so many things that are simply entered, for example, let's say disability insurance, or if someone wants to take out term life insurance, that things suddenly come to light that would be relevant for the insurance company, but perhaps not for the patient at that moment, and that could somehow be detrimental to the patient. I would have reservations about that." (I09, 57 – 62)

Morley *et al.*[44] explain what policymakers need to consider "if they are to enable health and care systems to capitalize on the dual benefits of ethical AI: Maximizing the opportunities to reduce costs, improve care and increase the efficiency of health and care systems, while proactively avoiding the potential harms." According to Morley *et al.*,[44] there is considerable research on the ethics of AI in health care and even for use in anamnesis. However, a defined set of ethical guidelines for AI usage in health care are currently unavailable, nor has every physician been educated about the essential ethical rules.

These propositions for further research address the complex dynamics and multifaceted considerations necessary when integrating AI technologies into health care. By pursuing these lines of inquiry, we can work toward optimizing the integration of AI in medical anamnesis, ultimately improving patient care and operational efficiency in health-care systems.

It is important to note that while AI shows promise in enhancing medical anamnesis, some doctors expressed uncertainty about its precise impact on quality:

> *"Basically, I would say that I can certainly imagine that it can improve efficiency and quality, but to what extent, I can hardly answer that now"* (I04, 43ff)

This uncertainty underscores the need for rigorous, empirical research to quantify and qualify the benefits and potential drawbacks of AI integration in health-care settings.

Although the initial reception of AI in medical anamnesis appears positive, there remains a significant need for further research to address concerns, optimize implementation, and ensure that the integration of AI truly enhances patient care without compromising the essential human elements of medical practice.

5. Conclusion

"Our intelligence is what makes us human, and AI is an extension of this quality." Yann and Joaquin Quiñonero.[45]

In conclusion, the analysis of the interviews reveals that doctors see significant opportunities and potential in AI-supported anamnesis, particularly for enhancing the speed and precision of medical history taking. Many doctors highlighted the potential for automating routine tasks, thereby freeing more time for direct patient care. The availability of up-to-date medical data through AI tools was seen as a key factor in improving treatment quality. The results indicate that doctors view AI-supported medical history-taking as a means to increase work efficiency and improve patient care.

Overall, all surveyed doctors expressed openness to integrating AI in medical history taking, with 100% willing to use AI tools in their daily practice. For instance, all respondents could envision working with tools such as Idana. The interviews underscored that AI-assisted medical history-taking eases doctors' workloads and enhances treatment quality, with time-saving and increased efficiency being the frequently mentioned advantages. The integration of AI tools into daily practice was met with broad interest and curiosity, alongside a fundamental willingness to accept technological support.

The study has some limitations. Due to the small sample size, self-selection of participants, and regional limitations, the study is not representative of all German physicians. In addition, the limited survey period of 2 months must be considered a limitation. The literature used was researched and selected by the authors and therefore cannot be assumed to be exhaustive.

The study also highlights several concerns. Issues related to data protection necessitate regular reviews of the technology and security mechanisms. In addition, six out of nine respondents identified patient constitution, particularly age, as a potential obstacle. Concerns were also expressed about the impact on the doctor–patient relationship, with fears that AI could lead to a loss of patient trust.

In summary, while AI technologies present promising advancements for medical history taking, careful consideration of the associated risks and challenges is essential for their successful integration into health care.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: All authors
Formal analysis: Marina Schellhorn
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Resources: Felix Höpfl
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Supervision: Felix Höpfl
Validation: Felix Höpfl
Visualization: All authors
Writing – original draft: Marina Schellhorn
Writing – review & editing: Felix Höpfl

Ethics approval and consent to participate

All interviewees were invited to participate in this study and provided their consent voluntarily. At the beginning of each interview, participants were explicitly asked whether they agreed to take part in the study. Their responses were recorded as part of the interview process. Participants were informed that their participation was entirely voluntary, that they could withdraw at any time without consequences, and that their responses would be anonymized and used solely for research purposes.

Consent for publication

All interviewees provided verbal consent to participate in the study, which was recorded at the beginning of each interview. No personal or identifying information was collected, ensuring participant anonymity. The study does not include any images or directly identifiable data of the participants. Therefore, no additional written consent for publication was required.

Availability of data

The interview transcripts are available on request from the authors.

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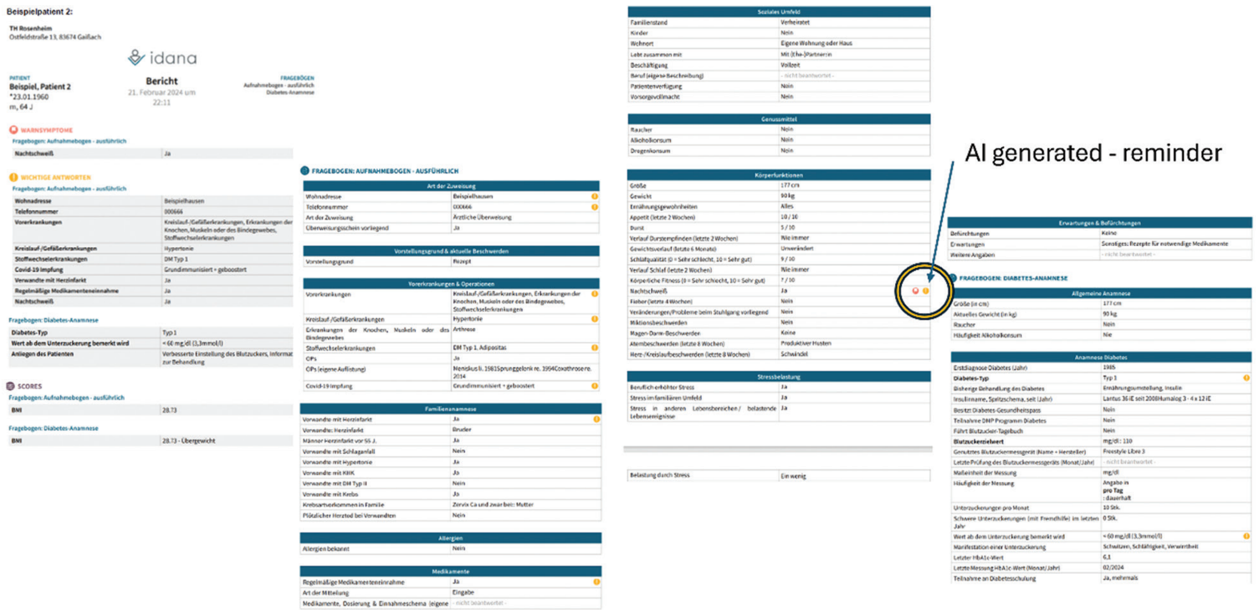
Appendices



Appendix A: Idana's screenshots

Appendix B: List of doctors

Interview number	Years	Medical specialty	Professional status	Institution	AI experience
1	35	Internal medicine, cardiology	Specialist	Hospital, cardiology department	Not available
2	51	Ear, nose, and throat specialist, special ENT surgery, facial plastic surgery	Registered physician with own practice	Private practice in group practice	Available
3	35	Gastroenterology	Registered physician with own practice	Two private practices, gastroenterology department	Available
4	59	Conservative orthopaedics	Registered physician with own practice	Private practice	Available
5	51	Orthopedics	Specialist	Rehabilitation clinic, pain therapy department	Not available
6	33	Rehabilitative, physical medicine, neurology, psychiatry	Assistant physician	Rehabilitation clinic	Not available
7	45	Neurology, emergency medicine	Assistant medical director	Rehabilitation clinic, rescue service	Available
8	54	General medicine	Registered physician with own practice	Joint practice	Not available
9	56	Neurology	Specialist	Rehabilitation clinic, neurology department	Not available
				56% working in hospital	56% not available
				44% registered physicians with own practice	44% available

Abbreviations: AI: Artificial intelligence; ENT: Ear, nose, and throat.

ACCSCIENCE PUBLISHING

Design+

SHORT COMMUNICATION

An "appropriate" education for a practice-based evidence approach in design education

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Abstract

Design occupies a space between theory and practice, strategy and tactics, discipline and craft. Its approach is now applied across a wide range of formulas and contexts. To maintain its ability to engage with reality, design must adopt an interpretation that manages increasingly complex models, while suggesting future educational frameworks. The objective of design is to practically intervene to modify reality, which makes its disciplinary dimensions somewhat ambiguous: It is rich in tools but lacks the foundational axioms of a discipline. A transdisciplinary perspective can be valuable in developing a reliable model and an affordable methodology. However, this perspective must be built on areas of knowledge in which the practical activity complements the theoretical evidence; that is, fields where the engagement with the public (both collectively and individually) is strong. Therefore, a stimulus can come from personal care practices such as medicine, psychology, or pedagogy. In these areas, recurring patterns (or, better, Gestalt) can help shape an anthropological dimension, one that reflects the contextual and functional nature of design.

Keywords: Education; Tool; Discipline; Practice; Evidence; Experience

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1. Introduction

The design of educational programs for design requires special attention due to the nature of the field, which exists between theory and practice, and between strategy and tactics. Design encompasses both speculative and conceptual components, but its full expression occurs through practical activity, whether this is temporally aligned with the theoretical or not. A concept may be applied at a distance, or even remain unapplied, yet still provide guidance for future actions. This is a historical reality, made more complex by the accelerating changes in social, economic, and, in recent years, health contexts – all of which can be involved in design processes. To be effective, an educational path must reveal the way to achieve results. In the context of design, which aims to provide real-world solutions, it is appropriate to clarify the methods for achieving pragmatic goals.

Despite its broad spectrum of applications (or perhaps because of it), design remains a tool rather than a discipline. It is not a normative system based on its own rules, whether derived from experimental scientific disciplines or speculative humanistic observations. However, it is an exceptionally versatile tool – or rather, a set of tools – capable not only of achieving specific objectives but also of generating solutions applicable across different contexts.

Thus, the relationship with problem-solving has evolved. In the current context, problem-solving is now closely intertwined with problem setting and problem finding (or even problem inventing, a concept often associated with future-oriented sciences). The first concerns circumscribing the problem, while the second focuses on predicting it (and the third on dealing with abstract hypotheses). This evolution has led to the prominence of certain keywords: design thinking, flexibility, and, in education, learning by doing – an approach that undoubtedly represents a canonical and historical reference. The concept of learning by doing, introduced by Dewey[1], originated within the American pragmatist school that also gave rise to the concept of abduction, as suggested by Peirce[2], which is particularly valuable to design scholars.

Abduction, in fact, opened a new perspective on how we understand knowledge. Positioned outside the deductive and inductive logics, which form the basis of any disciplinary model, abduction generates hypotheses, not certainties. In everyday design practice, this concept is exemplified by the "what if?" question.

By referencing Dewey and Peirce, we aim to propose a relationship between design practices and two disciplines that are similarly linked to a pragmatic dimension: Pedagogy, which includes a philosophical component and addresses educational models and their practical outcomes; and semiotics, which, in this case, transforms from a largely abstract discipline into a tool for reading reality in functional terms.

In other words, we are advocating a transversal interpretation that assimilates the methodological structures of different disciplines through design – a transdisciplinary hypothesis regarding the cultural peculiarities of design. This interpretation implies that the concept of transdisciplinarity, particularly crucial for scientific and humanistic disciplines, requires a specific interpretation when applied to design. Design, in fact, appears to be one of the few tools capable of triggering homologies suitable for constructing transdisciplinary frameworks.

If we are to be concise (perhaps overly so), design is necessarily transdisciplinary because it is not, in itself, a discipline. According to the concept of transdisciplinarity, the intersection and fusion of different disciplinary models represent a more than fertile scientific and hermeneutical horizon today. However, it must be managed correctly at the application level. The theme of design is not scientific evidence but pragmatic activity. Thus, reference models cannot be purely epistemological but should be linked to areas of knowledge that share a common problem: The relationship between theory and practice. This also means guaranteeing considerable variety and flexibility in approach, especially during educational phases. Consequently, we must consider the role of designers in design training. To prevent an approach that attempts to be scientific (but lacks a disciplinary model) from automatically becoming academic in the negative sense of the term, we must recognize that if training prepares students for a profession, the logic of the expert – who transforms the experience into a norm – can lead not only to an "academic" attitude but also to a vicious, self-referential cycle. This is particularly dangerous in a complex and urgent context, where the proliferation of tools risks becoming ineffective (or even harmful) if used improperly.

The risk is particularly evident in the application of inadequate explanatory structures in scientific communication within design research. The pursuit of objective conclusions in papers presented at international conferences often mimics the outcomes of scientific experiments conducted in laboratories. However, the design does not function *in vitro*, as its "discoveries" are always contextual and linked to specific situations. The role of references, too, should be subjected to specific conditions. A reference may be something freely utilized, as designers do when drawing on anything pragmatically to solve a problem (in terms of texts, patterns, styles, iconographies, etc.), or it should be a canon to devoutly adhere to. References are useful for building a "style" of thinking (and designing), which ultimately forms a methodology. However, are they mere abstract reference systems? Style is not a neutral term, nor is it limited to ornamental concerns. On the contrary, style is a complex interface that expresses cultural and anthropological relationships through artifacts.

2. Materials and methods

Dewey and Pierce are two historical references that help propose the idea of design as an activator of structural analogies between disciplines, aimed at interacting with the human dimension – an area in which design plays a significant role. This is a problem that design shares with other fields, particularly those where the relationship with the user or interlocutor is particularly strong, such as healthcare. In healthcare, for example, there is a need not only to find practical solutions based on documented premises but also to monitor the results achieved, to develop increasingly effective tools.

From these specific needs, a true transdisciplinary hypothesis could arise. This hypothesis would not rely on certified laws or data from different scientific contexts but on the potential application of such data in hypotheses and models. In clinical practice, for example, the evidence-based practice (EBP) model – which is based on the data evidence – must be balanced with the practice-based evidence (PBE) model, where practice reshapes research[3]. This balance involves reconciling what the data have shown (available through scientific studies and, in professional practice, market research) with the need to focus on the implications of the individual case.

Therefore, the issue is not one of induction or deduction, but of abduction, that is, contextualizing the data derived from research in practice, while considering the importance of the individual case and of the *hic et nunc* (here and now). The crucial problem is not adhering to the rules outlined by scientific evidence but finding the best solution to the specific problem at hand. The solution does not merely provide further data but redefines how data are acquired, interpreted, and utilized. To exaggerate slightly, this is akin to a "theory of practical arts" (according to De Certeau)[4], where practical interpretation constructs models (tricks, rituals, methods, etc.) that guide everyday actions related to daily life. For design, this takes the form of workshop activity, which historically has been central to the typical educational approaches of fine arts and design schools.

Hence, can we maintain a balance between the two models, PBE and EBP? Certainly, considering a design process based on an EBP model suggests adopting conservative solutions that replicate results already achieved. This situation often occurs in the professional practice of designers, especially when the client's wishes prevail – such as when they seek to implement their own ideas, follow a celebrated example, or prioritize maintaining market share.

However, if we are referring to design as a tool for innovation, this model is less suited to describe its approach. In such cases, the "what if" (or "if-then") test becomes necessary. Moreover, in the context of education, in a period marked by constant and increasingly intense crises, this balance can no longer be sustained, as (for instance) the two "First Things First" manifestos from the 1960s and 2000s have already suggested[5].

These documents remind us that whenever we convince ourselves that design can truly solve collective problems, we risk disillusionment by making improper generalizations or abstractions of its scope. Design operates within an eminently cultural sphere, which is inherently slow or resistant to change. This is why the quote by Paul Hogan, founder of the "Design for All" movement (focused on inclusive design) – "Good design enables, bad design disables"[6] – remains painfully true. This point must be fundamentally acknowledged in design education.

Thus, design is a tool essential for activating transdisciplinarity in various contexts, as it plays a key role in establishing relationships with the external environment, which in turn shapes the personal, social, and cultural dimensions of individuals. It provides a way to transform theoretical approaches into practice by building relationships that influence behaviors and give them new meanings. Whether the object of intervention is products, services, communities, communication artifacts, policies, or others, the model does not simply foresee the adaptation of an existing program, but rather the creation of a process that is always ready to shape the practice of these relationships through design and educational methodologies. This model aligns with one of the most intriguing transdisciplinary approaches, which uses anthropology as a bridge between biology and psychology, as Ingold suggests[7]. It is no coincidence that anthropology, a discipline concerned with culture and its symbolic expressions, also applies to everyday life, human behaviors, and material culture – precisely the domain of design.

3. Results

Design education must developed in such a way that it constructs an "anthropology of practice", both in the physical world and the virtual realm.[8] This approach should be capable of engaging with the search for deep patterns in human cultures that recent anthropology has been pursuing.[9] These patterns can be applied both to the mechanisms of production, particularly in creative industries (CIs), and to their organizational structures. From the first perspective, the basic processes of elaboration in CIs remain unchanged, although the scope of production can be vast and highly differentiated. One example is the "new craftsmanship," or more accurately, the craftsmanship approach adopted by individuals working in the digital world.[10]

On the other hand, CIs are characterized by an organizational model that is radically different from that of traditional industries. They are also marked by a revival of the concept of community, albeit with features that differ significantly from their original forms, especially in terms of temporality.[11]

Since practice-led activities have long been regarded as a common denominator between CIs (with design being one of their earliest representatives) and applied university research,[12] this is another aspect that the educational system must address. This includes promoting a continuous revision of CI value propositions.

CIs are indeed linked to models that are entirely different from traditional industries – transitional models, which are project-based rather than organization- or network-based.[13] We could refer to these as "cloud" models or, following Bey's definition, "canvas" models.[14]. In this context, it is possible to apply a series of definitions that interact with the previously mentioned concepts of PBE and EBP to the field of design and design education. This, in turn, provides a model for the goals that an educational program can aim to achieve. We can apply this working hypothesis on an educational level to define the possibilities for intervention in various areas claimed by design in recent decades while maintaining the contextuality and scalability of the approach.

The terms "efficacy," "effectiveness," "efficiency," and "appropriateness" as used in both economic (Drucker)[15] and clinical (Cochrane)[16] contexts, provide a valuable framework, especially in a situation where the entire social context – and the educational system within it – has been disrupted by the current pandemic. Efficacy and effectiveness relate to the two models, EBP and PBE, mentioned above: the former involves the application of a program (or protocol), while the latter refers to the transformation of good practices into recommendations. Efficiency pertains to achieving a goal with the least possible effort, and appropriateness involves the right intervention (at the right time, with the right user, and in the right way).

4. Discussion

It is often said that every crisis leads to system evolution. The pandemic forced organizations to confront the urgent need to adopt new procedures. This context was also true education, which saw a rapid shift to remote working, digitalization, and the use of new tools and practices. More than just technological or organizational change, this represented a shift in the design of education – a particularly important development for those involved in design education.

During the pandemic lockdown, the Postgraduate School of Instituto Europeo di Design (IED) Milano initiated a series of practical hypotheses, drawing on the input from its Coordinators. These emergency solutions not only addressed immediate needs but also stimulated broader discussions about the very rapid evolution of CIs. Therefore, these solutions proved valuable tactically, in redesigning curricula and creating new workflows, and strategically, in identifying approaches to tackle a phygital (physical plus digital) future. This transition was becoming the norm for stakeholders in educational projects, including both private and public organizations. It is worth noting that since its founding in 1966, IED has been committed to collaborating directly with companies and institutions to develop concept design programs. This reflects a long-standing engagement in a PBE approach.

The series of hypotheses developed during the pandemic evolved into guidelines: They were not simply applications of pre-existing protocols, but rather elements of a dynamic process. In response to the need for rapid and practical action, the goal was to use mnemonic tools to reorganize design activities within work groups – a characteristic approach of the institution. These guidelines can be summarized through a few key terms, each supported by secondary keywords, relevant statements, and guiding mottos, all organized in a functional sequence.

Considering the current situation, the first keyword chosen was "Adaptation," with sub-keywords including strategy/tactics, resilience, and flexibility. These terms are concerned with situations in which a well-designed process is subjected to sudden changes due to unforeseen events, requiring a reconfiguration of the guidelines' effective application. Such situations would be impossible to address with rigid protocols). This can be encapsulated in the motto: Design as a blend of strategy and tactics.

The second keyword, "Workout," brings together the concepts of exercise, practice, and open process. Continuous training in design methodologies allows for tackling complex projects through intense practice and iterative revision. The corresponding motto is: Design as a complex toolkit.

The third keyword, "Ability/skills," refers to competencies, skills, and alignment. In a cloud-based context, every individual brings their own skills and networks, "glocalizing" their intervention based on a specific substratum of knowledge and contacts, which are then realigned to the collective effort. A possible motto for this concept is: Anthropology of techniques.

The fourth keyword, "Self-production" encompasses the "Do it yourself" (or "Design it yourself") technique and democratization of technologies. Project phases can be developed remotely by students and integrated into the workflow. The motto "Design it yourself" can be particularly significant even in professional terms, expanding upon the original definition by Lupton[17].

The final keyword, "Cloudiness," refers to project elasticity and transience. Classes and working groups, in fact, are transient communities: they form, disband, and re-form according to a non-definitive model. The final motto, which should also be understood in practical terms: Cloud/canvas versus network.

After the pandemic emergency, during which these mnemotechnical tools were employed out of immediate necessity and urgency, it became essential to reflect on the experience, which extended beyond the aforementioned list that emerged from the activities of various courses. In response to the points above, we aimed to construct an educational model – definitely not stable enough to be called a methodology – that could transform the experience into repeatable actions and strategies. This effort sought to define the theoretical background for the concepts mentioned earlier.

The pandemic highlighted the possibility of using different tools and practices, but it also exposed particular tendencies among students, along with original methods in the genesis of their projects. This situation prompted us to establish a broad-based reference system, adaptable to the specific needs of various programs. The Post-graduate School, for instance, offers 1-year program with a strong professional orientation. During the same period, IED launched its first Master of Fine Arts in Transdisciplinary Design, which provided an opportunity to rethink a new methodological approach.

To start from the basics and allow for maximum adaptability, the initial references were drawn from psychology and pedagogy, with a reflection that had to encompass all aspects of the educational process.

First, we considered the creation of an environment rich in stimuli, one that fosters the development of the student's creative abilities. The reference here is to Winnicot's[18] concept of the transitional object, which enables young children to form a sense of autonomy and identity separate from their primary relationship with the mother. The objects help children create connections with the surrounding world that they can claim as their own. Similarly, tools — both technological and conceptual — serve this purpose in the educational context.

Second, we explored Bion's[19] approach to training, which involves the transformation of raw experience into organized systems and narratives. A system can be a useful metaphor for both defining the design approach and understanding its impact. The theme of narrative also reminds us of the importance of a humanistic interpretation of the project during its operational phase, as well as the utility of storytelling in its communicative phase.

Finally, we considered Piaget's[20] view of education, which he derived from his daily observations of his children. His work emphasizes the relationship between the assimilation of external data and the accommodation of this data within a framework based on a constant interplay between practice and evidence. This approach also involves constructing a style of thought and action, as De Certeau[21] understood it.

5. Conclusion

The educational objective is to prepare students not only to become professionals but also to act as catalysts within their contexts – activating resources, building networks, and identifying, defining, and solving both dormant and existing problems.

These aspects are evident in the design training model, where the laboratory setting plays a central role in the acquisition of knowledge. This model applies a transdisciplinary perspective that emphasizes the integration of social, economic, and even political contexts, as demonstrated, for example, by the Master's program offered by the School of Visual Arts in New York.

Ultimately, this approach redefines disciplinary boundaries, extending beyond academic contexts (Van der Bijl-Brouwer). It also expands the metaphors surrounding the role of design itself, whether as "binding glue" (again, Van der Bijl-Brouwer), a mediator and provocateur (Geenen), or as "water-tracing dye" (Gaudio, Hallgrimssona, and Marshal), as outlined in *Design Methods and Transdisciplinary Practices*, the 2022 edition of the Design Research Society Conference Series.[22]

In short, as the scope of design expands to encompass a wider range of contexts and practices, the skills of designers must evolve. These skills must integrate disciplinary knowledge that cannot be fully mastered by any one individual in the profession. The key question, then, is whether design can serve as a structural and structuring mediator that respects the diversity and depth of this knowledge. Design must balance, on the one hand, adopting a point of view common to disciplines that share a practical focus, and, on the other hand, leveraging its well-established ability to break boundaries and establish analogies between different fields, shaping knowledge itself as a malleable material.

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ACCSCIENCE PUBLISHING

Design+

SHORT COMMUNICATION

A feasibility study of shell fusion technology application in jewelry design

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Abstract

In recent times, to cater to a larger audience, mass production has become more common, with investment casting being one of the fastest-growing manufacturing techniques. However, even with this modernization, production still requires significant manual labor, such as mold assembly, heating, gas removal, cutting, and polishing. This process also consumes a lot of energy and generates waste. Rapid prototyping and computer-aided design technologies have revolutionized jewelry manufacturing, enabling greater agility, reduced production time, and product customization, while also offering designers more creative freedom. This study aims to present shell fusion technology (SFT), an advanced digital manufacturing technology, as a way of processing jewelry and other precious metals for various applications. Practical processing tests were carried out using SFT. Metallic materials with high and low melting points were employed, enabling the investigation of processing characteristics (temperature, heating rate, and melting time), final quality (flaws, roughness, etc.), finishing requirements, and other factors. The feasibility of making jewelry and metal parts using SFT was investigated and validated. This work demonstrates that SFT can be used to make jewelry and process noble metals for other purposes. A piece of jewelry was produced with a quality classified as satisfactory for use as an ornament.

Keywords: Shell fusion technology; Advanced digital manufacturing; Jewelry

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1. Introduction

Conventional jewelry-making processes are frequently linked to arts and crafts practices in the jewelry manufacturing industry. For a considerable amount of time, factories have endeavored to optimize procedures that require a lot of labor, time, and expertise.[1] In some traditional jewelry companies, only close relatives are privy to the entire production process, which concentrates this information within a small number of family groups. For these companies, each piece of jewelry is meticulously crafted to ensure that it is exquisite and of the highest caliber for a very specific person. In recent times, due to the need to cater to a larger audience, the use of mass production technologies has increased as a way of meeting this demand. The investment casting process has been one of the fastest-growing manufacturing systems for jewelry production.

With the use of such technology, jewelry manufacturing has become more agile and capable of serial production. However, even with the advent of mass production capacity, to obtain jewelry in its final condition, this type of processing still requires a lot of manual labor, such as building the trees and feed channels, moving between the heating processes, making the coating barbotine, applying a vacuum system to remove gases, cutting the feed channels, deburring, and polishing, among others. The process of melting and oxidizing the wax requires intense heat application, which must be maintained for the next processing stage, i.e., the pouring of liquid metal.

The metallic material is previously being melted in another furnace and kept above the melting temperature, allowing the metal to remain in a molten state. The metal can then be poured to fill the mold cavity. This series of procedures uses a lot of equipment and consumes a lot of time and energy to prepare the mold and melt the metals, as well as produce a lot of waste that cannot be reused in a new cycle. Rapid prototyping and computer-aided design (CAD) technology have revolutionized jewelry design and manufacturing, as they have enabled significant advances. These technologies also work to reduce the time needed to build models and allow jewelry products to be made in various sizes, with personalization or customization.[2,3]

Greater creative freedom for designers, lower environmental impact, and greater economic efficiency are all possible results of integrating additive manufacturing (AM) techniques into conventional jewelry manufacturing processes. Energy use, labor hours per unit, and waste and recycling expenses can all be reduced with the use of AM processes. In addition, more geometric freedom can help designers without sacrificing the viability of the final product.[2,3] AM technologies have been incorporated into several sectors in recent times, resulting in increased industrial capacity and optimization.[4]

In addition, AM technology has been used in several jewelry-making processes, including prototype development, low-volume jewelry manufacturing, wax or master printing, and fashion final goods.[1]

However, even the most advanced AM processes still have limitations, such as excessive use of support material, high cost of material in the form of powders, equipment with high acquisition and processing costs (use of gases, auxiliary heating systems, and removal of non-sintered powders), and long debinding and sintering times (to avoid deformation in parts made by stereolithography slurry), among others.

The new shell fusion technology (SFT), which is aligned with the AM trend, may be viewed as an indirect AM or an advanced manufacturing method because the component is not produced directly; rather, a composite material shell/mold with the cavity in the intended format is created, allowing the part to be obtained in its final format.

SFT offers many benefits over conventional methods, including the capacity to produce intricate components for a range of applications, low-cost processes and equipment, decreasing the amount of material support, and expanding its application into the jewelry sector. This study aims to improve jewelry manufacturing by including freeform and conceptual innovation, using SFT as a concept test and facilitating metallic alloy processing.

In general, the current methods applied in jewelry metal fabrication are based on metal casting. New proposed methods, such as selective laser sintering and selective laser melting, are unable to support noble and high-noble metal alloys.

Metal casting is a crucial process in jewelry making for shaping molten metal into intricate designs. The most common method for metal casting in jewelry making is lost-wax casting, also known as investment casting. This technique involves creating a wax model of the jewelry piece, which is then encased in a plaster-like material. Once the mold is heated, the wax melts away, leaving a cavity that is filled with molten metal to form the final piece. The other top methods include sand casting, where sand is used as the mold material; centrifugal casting, which utilizes centrifugal force to distribute the molten metal; vacuum casting, which draws the molten metal into the mold using a vacuum; and die casting, where metal is forced into a mold under high pressure.[5-8]

Digital methods have revolutionized the jewelry-making process, offering precision and versatility that were previously unattainable. Computer numerical control (CNC) machines allow for precise cutting and shaping of metals and other materials, following a programmed design. CAD software is used to create detailed 3D models of jewelry pieces, which can then be used to guide both CNC machines and computer-aided manufacturing (CAM) processes. 3D printing has also become increasingly popular in jewelry making, allowing for the creation of intricate designs that are difficult or impossible to achieve through traditional casting methods. This technology can produce wax models for lost-wax casting or directly print the jewelry piece in metal, providing both flexibility and accuracy in the creation of custom jewelry.[5-8]

The digital flow for jewelry making involves 3D scanning to capture the design, 3D modeling using CAD software, and developing a manufacturing plan with CAM software, followed by fabrication and finishing.

In Table 1, the production rate is expressed in terms of the type of manufacturing process and sort of

Table 1. Production rate of different processes for different materials

Material	Production rate (unit[s]/h)						
	Manual	CAD/CAM casting	Lost wax	SLA casting	SLA slurry	SLM	SFT
Ceramic	<0.5	-	1	-	<0.1	-	1 – 10
High-noble metal alloy	<0.5	1 – 2	1 – 50	0.5 – 10	-	-	1 – 10
Noble metal alloy	<0.5	1 – 2	1 – 50	0.5 – 10	-	-	1 – 10
Predominately base-metal	<0.5	1 – 2	1 – 50	0.5 – 10	-	1	1 – 10

Note: Data were obtained from references.[6-9]
Abbreviations: CAD: Computer-aided design; CAM: Computer-aided manufacturing; SLA: Stereolithography; SLM: Selective laser metal; SFT: Shell fusion technology.

material. Therefore, it is possible to identify either the low productivity or lack of capability of the manufacturing processes with regard to jewelry making.

2. Material and methods

Using the appropriate software, jewelry designs are first created, sketched, and then converted to CAD format. Figure 1 displays a design model that can be processed utilizing SFT. The components of the 3D model utilized to create the shell with the intended form are also displayed in Figure 1, including the mold-forming portion, the gas feed and release channels, the reservoir area of the metal material to be cast, and the channel feed. After obtaining the CAD file, it may be converted to the STL format, and the required modifications performed for the shell creation process can be later converted to CNC machine language.

The specimens are created using SFT, which results in shells with an average composition of 80% $ZrSiO_4$. The shell is produced from the feeding channels, and the appropriate mold subsequently forms. After generating the shell, the quality of the impression is checked by visual and geometric analysis according to the design. The metal fragments to be melted are deposited in the shell reservoir region. This assembly is then positioned in a refractory container filled with thermally conductive material in the form of ceramic powder.

The container is filled with metal beads, and the shell produced is then positioned in an electric furnace for debinding (removal of the organic charge present in the shell), followed by simultaneous material melting and shell filling. One of the advantages of the SFT process is that, during the debinding process of the polymers present in the composite forming the mold/shell, there is an intense release of gases from the decomposition of the organic part.

These gases remain present during the debinding process and also during the initial stages of melting the metallic material. As in the case of tin alloys and other materials with a low melting point, pulling can occur concurrently with melting and filling the mold, depending on the type of particulate metal material employed in the

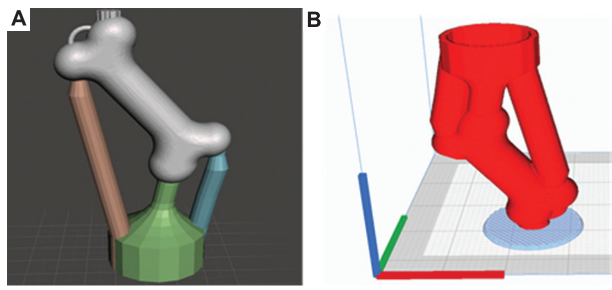

Figure 1. 3D models for SFT process. (A) Schematic of filling channel and jewel part orientation. (B) Schematic of the shell mold.

process. On the other hand, materials and alloys with higher melting points, such as stainless steel, Cu, Au, Ag, Pt, Ni, and their alloys, take longer to reach their melting point. After melting, the part is cooled before being removed from the mold, allowing the object to be readily separated and, if necessary, polished or sharpened. The presence of this gaseous atmosphere exerts isostatic pressure on the system, increasing the mechanical strength of the jewelry produced and reducing the surface roughness of the piece, thereby improving its final appearance. Various tests were carried out to determine the optimum operating conditions for processing the mold to be produced (Table 2).

The SFT process is represented in Figure 2, encompassing the initial visualization of the jewelry design stage using CAD (Figure 1). The shell is manufactured with the desired mold shape, and the particulate material is subsequently positioned to enter the mold at the time of melting.

The material chosen for testing was a silver alloy, which is commonly used to make prototypes, as it is economical, soft, and easy to work with.[9] A 3D scan of a piece in the shape of a dog bone jewel was made and transferred to Meshmixer software, where corrections, adjustments, and the addition of accessory systems (reservoirs, feed, and vent channels) were made for processing the shell. The generated STL file was then transferred to Zirconium Medical Devices' Ceramic Slicer software, where it was converted into G-code format and sliced; the ceramic shell mold was then produced.

The debinding and sintering processes were regulated by a 1600 W electrical Furnace PID controller with four ramp curves and an insulation muffle, with sintering conditions at 1130°C for 60 min. The sintering and debinding curves are presented in Figure 3.

3. Results and discussion

Certain aspects of SFT can be compared with competitors' processes, revealing significant distinctions between SFT and investment casting.

The investment casting process uses CAD/CAM systems to produce wax models, which speeds up the modeling process but requires a lot of manual work to mount the pieces on the trees and place the feed channels.

For the mold cavity to eventually develop, the tree must be coated with refractory ceramic suspension. The assembly is placed in an oven to remove the wax and thermally cure the plaster cast, creating a mold that is ready for liquid metal pouring. After the liquid metal is poured, the tree solidifies, and its parts must be taken out of the feed channels before deburring and final finishing.

Table 2. Parameters of shell manufacturing

Variable	Fixed condition
Material temperature (°C)	30
Chamber temperature (°C)	75
Extrusion temperature (°C)	210
Layer thickness (mm)	0.2
Gap between fabrication lines (mm)	0.2
Tool diameter (mm)	0.6
Aided gas flow (m/s)	0.1
Ambient temperature (°C)	25
Relative humidity	0.3

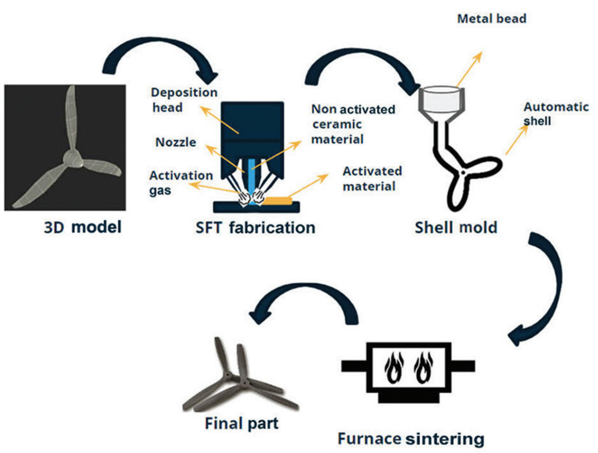

Figure 2. Scheme of the shell fusion technology process

A characteristic of the investment casting process is that, due to the need for feeding, venting, and pressurization channels, much of the molten material is not used in the production of the part, and even if it is reused later, there is a lot of energy and financial loss in the manufacturing process.

The SFT method is more automated and requires fewer stages to produce the finished product. The mold cavity is created immediately; curing procedures and refractory linings are not required. Only debinding and liquid metal melting are required to complete the shell's construction. Without the need for manual operations, the two occurrences take place within the heat treatment furnace one after the other.

The pre-sintered shell/mold is then cooled, making it easier to break apart and remove the inside component. This operation can be completed quickly by hand without the need for specialized instruments, while strongly attached mold particles can be removed with a brush.

It is feasible to obtain a piece of silver for ornamental purposes through the STF procedure, as presented in Figure 4. To achieve better results in terms of the surface

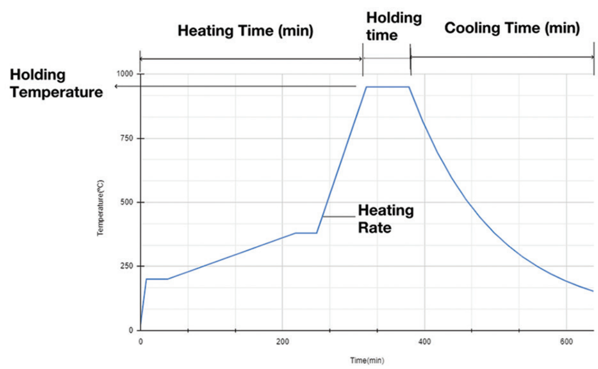

Figure 3. Temperature curve of the furnace for material sintering used in this study

Figure 4. A silver piece manufactured using shell fusion technology

finish of the part, it is necessary to make some adjustments to the process parameters, thereby reducing the finishing time of the part. The production capacity of the SFT process depends solely on the size of the furnace and its capacity to accommodate the shells and thermally conductive material.

Further studies are warranted to obtain the technical and economic characteristics of various jewelry manufacturing processes and compare them with SFT.

4. Conclusion

The primary aim of this study was to assess the feasibility of SFT for producing metal jewels. The results indicate that the SFT technique may be used to manufacture silver jewelry, as seen by the high quality of the final piece, which had good geometric uniformity and surface finish. In addition, a brief analysis of alternative approaches to metal jewel manufacturing was conducted. Additional studies are warranted to improve processability and identify process limits, in terms of size, thickness, surface quality, and other factors. During development, questions emerged about the economic viability of this method compared to other methods of producing metal ornaments, necessitating additional research.

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Conflict of interest

The authors declare no conflict of interest related to this work.

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Writing – original draft: All authors
Writing – review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Availability of data

Data are available from the corresponding author upon reasonable request.

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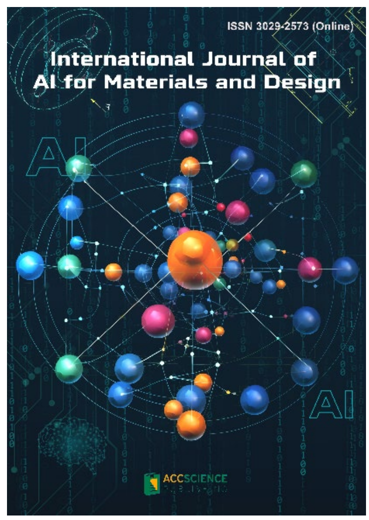

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