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Leveraging AI for the Recreation and Restoration of Ancient Indian Costumes and Accessories

Uporaba umetne inteligence za rekonstrukcijo in restavriranje staroindijskih oblačil in modnih dodatkov

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Abstract

The restoration and recreation of ancient Indian costumes and accessories are critical for preserving the nation's rich cultural and historical heritage. This review explores the transformative role of artificial intelligence (AI) in studying and interpreting primary data sources to revive traditional attire and accessories from ancient India. Primary data sources, such as textual manuscripts, sculptures, iconography and archaeological findings, offer invaluable insights into ancient fashion. Yet, their interpretation is often complex, time-consuming and prone to human error. AI, with its advanced computational capabilities, has emerged as a promising tool to analyse and reconstruct these historical artifacts with remarkable accuracy and efficiency. This paper discusses the various applications of AI, including machine learning, computer vision and natural language processing, in decoding the intricate patterns, designs and cultural elements embedded in historical data to achieve accurate results. For instance, AI-powered image recognition tools and computer vision algorithms can analyse sculptural depictions to extract information about garment textures, draping styles and accessories. Natural language processing algorithms can decode ancient textual data, such as ancient scriptures and inscriptions, to understand and extract references to fabrics, dyeing and weaving techniques, ornamentation methods and the symbolic meanings of costumes. Even archaeological findings and reports, including remnants of textiles and ornaments, can be studied using AI for material composition analysis and virtual reconstruction. These technologies not only enable the recreation of visual representations of ancient attire but also provide insights into the socio-cultural and historical contexts of the time.

This paper also highlights the challenges associated with integrating AI into this area, such as the limited availability of digitized primary data, the need for culturally sensitive algorithms and technological constraints in interpreting incomplete or degraded data. Despite these challenges, interdisciplinary approaches involving AI, history, design and archaeology hold immense potential to revolutionize the restoration of ancient Indian costumes. Despite these barriers, this study highlights the transformative potential of interdisciplinary collaboration among AI specialists, designers, historians, and archaeologists, and how technological innovation can support the accurate recreation of ancient Indian costumes and contribute meaningfully to the conservation



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and dissemination of India's cultural heritage. The findings suggest that AI-driven methodologies can not only aid in the accurate recreation of ancient attire but also ensure the sustainable conservation of India's cultural legacy for future generations.

Keywords: ancient Indian costumes, artificial intelligence, costume restoration, cultural heritage

Izvleček

Restavriranje in rekonstrukcija staroindijskih oblačil ter modnih dodatkov sta ključnega pomena za ohranjanje bogate kulturne in zgodovinske dediščine naroda. Članek obravnava vlogo umetne inteligence (UI) pri preučevanju in interpretaciji primarnih podatkovnih virov, da bi oživila tradicionalna oblačila in dodatke iz starodavne Indije. Primarni podatkovni viri, kot so rokopisi, skulpture, ikonografija in arheološke najdbe, ponujajo neprecenljiv vpogled v starodavno modo. Njihova interpretacija pa je pogosto zahtevna, dolgotrajna in podvržena človeškim napakam. UI se s svojimi naprednimi računalniškimi zmogljivostmi uveljavlja kot obetavno orodje za analizo in rekonstrukcijo zgodovinskih artefaktov z izjemno natančnostjo in učinkovitostjo. Prispevek obravnava različne uporabe UI, vključno z metodami strojnega učenja, računalniškega vida in obdelave naravnega jezika pri dekodiranju zapletenih vzorcev, oblikovnih zasnov in kulturnih elementov, ki so vključeni v zgodovinske podatke. S slednjim bi dosegli natančne rezultate. Orodja za prepoznavanje slik, podprta z UI, ter algoritmi računalniškega vida lahko analizirajo kiparske upodobitve in iz njih pridobijo informacije o tkaninah, npr. teksturi, slogu drapiranja, in uporabljenih modnih dodatkih. Algoritmi za obdelavo naravnega jezika omogočajo razčlenjevanje starodavnih besedilnih virov, kot so sveta besedila oziroma spisi in napisi, da bi prepoznali in razumeli omembe tkanin, tehnik barvanja in tkanja, načinov okraševanja ter simbolnih pomenov oblačil. Tudi arheološke najdbe in poročila, med njimi ostanki tekstilij in okraskov, je mogoče preučevati z uporabo UI za analizo materialne sestave in virtualno rekonstrukcijo. Te tehnologije pa ne omogočajo zgolj rekonstrukcije vizualnih predstav staroindijskih oblačil, temveč ponujajo tudi dragocen vpogled v družbeno-kulturni in zgodovinski kontekst obravnavanega obdobja.

Članek prav tako izpostavlja izzive, ki so povezani z vključevanjem UI na področju, npr. omejen dostop do digitaliziranih primarnih podatkov, potreba po kulturno občutljivih algoritmih ter tehnološke omejitve pri interpretaciji nepopolnih ali poškodovanih podatkovnih virov. Kljub izzivom pa predstavljajo interdisciplinarni pristopi, ki združujejo UI, zgodovino, oblikovanje in arheologijo, izjemen potencial za preoblikovanje postopkov restavriranja staroindijskih oblačil. Raziskava poudarja pomen sodelovanja med strokovnjaki za UI, oblikovalci, zgodovinarji in arheologi ter prikazuje, kako lahko tehnološke inovacije prispevajo k natančni rekonstrukciji staroindijskih oblačil in hkrati pomembno podprejo ohranjanje ter širjenje indijske kulturne dediščine. Ugotovitve kažejo, da lahko metodologije, podprte z UI, ne le omogočijo verodostojno rekonstrukcijo starodavne noše, temveč tudi zagotovijo trajnostno varovanje indijske kulturne zapuščine za prihodnje generacije.

Ključne besede: staroindijska oblačila, umetna inteligenca, restavriranje oblačil, kulturna dediščina

1 Introduction

The vibrant history of ancient India is reflected in its costumes and accessories, which symbolize the country's cultural richness and artistic excellence [1]. As Ghurye states, the symbolic and aesthetic significance of Indian costumes and ornaments reflects ancient

India's cultural richness and artistic excellence [2], while studying historic costumes and textiles helps to understand cultural evolution and artistic expression in the Indian subcontinent [3]. Through the study and exploration of primary data sources, such as old

transcripts, manuscripts, sculptures and inscriptions, we can redefine, restore and recreate the drapes of the silhouette and details of the surface development techniques of ancient costumes, along with the intricate designs of the accessories used during these periods. Additionally, this study allows us to analyse the lifestyles, values and beliefs from that time, providing a valuable source of knowledge for researchers, designers and historians. However, most of the primary data sources (manuscripts and transcripts) remain unexplored or underexplored with the vision of studying historical costumes and accessories [4]. Illuminated manuscripts are an underexplored source of information about historical costumes and accessories [5]. Some historical facts, such as sculptures and inscriptions, cannot be analysed due to degradation and destruction caused either by the passage of time or by foreign invaders [6]. At the same time, some sources cannot be decoded in terms of their chronology due to the complexity of interpreting them because of a lack of textual sources and the scarcity of inscribed works upon them [7]. Therefore, recreating and restoring the costumes and accessories of ancient times is essential for preserving and understanding the rich cultural heritage of ancient Indian textiles, costumes and accessories for the benefit of future generations. To initiate a similar effort, it is essential to study and explore available primary data sources such as ancient manuscripts, sculptures, iconography and archaeological findings. Detailed descriptions of fabrics used, ornaments designed and clothing practices are found in textual records, including Vedic scriptures, inscriptions and literary works [8]. Textual records, including Vedic scriptures, inscriptions and literary works, provide detailed descriptions of fabrics, ornaments and clothing practices [9] while the intricate details of garment structures, draping styles, designs and materials used in accessories can be derived from sculptures and iconographic art as sources of visual representations [10]. Other sources include archaeological findings, such as remnants of textiles, jewellery and dye samples, adding material evidence to these historical narratives. However, interpreting

these sets of information requires a methodical approach, precision and interdisciplinary expertise, as these sources are often fragmented and complex to decode, and their manual interpretation can be very time-consuming and prone to inaccuracies. The role of AI is vital to enable the more efficient and accurate analysis of these data. It can also play a very important role during the restoration and recreation of ancient Indian costumes and accessories based on the analysed data.

Integrating AI into the study of ancient Indian costumes and accessories holds immense potential for the generation of results. It is possible to reconstruct historical garments with high precision, offering perfect visual representations by combining advanced technologies with traditional research methods. Machine learning and computer vision technologies facilitate automated pattern recognition, image analysis and visual reconstruction. For example, AI-powered image recognition can extract fine details from sculptures and paintings, such as garment textures and accessory designs. Additionally, AI simulations can recreate virtual models of ancient attire, helping researchers visualize garments in their original context. By automating repetitive tasks and uncovering hidden patterns in data, AI enhances the accuracy and efficiency of restoration efforts. For instance, GAN-based systems have been used to recreate traditional costume designs from historical datasets, while deep learning architectures have achieved over 97% accuracy in recognizing Indian textile patterns. Moreover, text mining and NLP tools are being employed to extract meaningful insights from Sanskrit manuscripts and Pali scriptures. In the Indian context, projects such as the National Mission for Manuscripts have paved the way for large-scale digitization, creating opportunities to apply AI models to ancient texts and iconography. However, despite the growing corpus of research, very few studies have focused on using AI specifically for the systematic restoration of traditional Indian costumes and accessories through multi-modal primary data sources.

This paper aims to explore the benefits of applying AI to the systematic study of the primary data sources required to analyse the designs and styles of costumes and accessories, along with patterns and motifs used for textile surfaces, with a collaborative and interdisciplinary approach to restore and recreate them by integrating advanced tools. Its purpose is to digitally reconstruct and preserve ancient Indian attire, ensuring the creation of an authentic resource to spread the legacy of this invaluable culture. These resources can be a landmark for heritage preservation, costume designers, historians, interdisciplinary academic researchers and virtual exhibitors.

2 Background and overview

Clothing and accessories serve as an intricate communication system, enabling individuals and groups to convey their identity across various social contexts [11]. Clothing and adornment held significant importance in ancient societies, serving as markers of identity, status and cultural values. They can be regarded as valuable tools for understanding social institutions and the concepts of rank, gender and status [12]. In the Indian context, extensive literary evidence is available that describes technology, trade, social structure, cultural identity, historical context, environment and geographical constraints. These shreds of evidence serve as a valuable resource, offering significant insights while connecting its threads to the use of ancient clothing, including textiles, costumes, jewellery and other accessories used in various scenarios of a specific time and place. Traditional Indian jewellery, with a history spanning more than 5,000 years, also reflects the influence of religion, social structures and economics on personal ornamentation [13]. Historical transcripts and manuscripts can be a gold mine for studying ancient Indian culture, including costumes, jewellery and accessories [14]. Sculptures from the Paramar period, such as those found in Bhopal museums, showcase the costumes and jewellery of various goddesses, offering a glimpse into the artistic

and religious traditions of that era [15]. In the context of ancient Indian costumes and accessories, AI offers innovative approaches to decode and revive these treasures that reflect the legacy of the nation's artistic excellence and cultural depth. Integrating mathematical and computational approaches can provide novel insights into cultural elements such as costumes and revealing patterns [1]. AI can also assist in analysing and presenting museum artifacts, enhancing their visual representation for various design purposes [16]. Artificial intelligence and machine learning are considered emerging powerful tools for preserving and disseminating cultural heritage. It can aid in the virtual restoration of tangible artifacts, such as paintings and sculptures, protecting them from environmental damage and decay [17]. Existing worldwide research and methodologies that leverage AI and their applications to study primary data sources (transcripts, manuscripts, coinages, archaeological insights, sculptures, etc.) are of historical relevance, and can also be used to recreate, restore and digitalize historical costumes and accessories leveraging these tools, with a focus on the ancient Indian era.

3 Exploration of primary data sources through artificial intelligence

Current research on the use of AI to analyse primary cultural data sources, such as manuscripts, sculptures and archaeological evidence, remains limited despite AI's potential in this area [18]. AI can demonstrate its emerging potential in automated pattern recognition, visual analysis and text extraction applications specific to cultural studies, especially costumes and accessories. The integration of AI in cultural heritage research facilitates data analysis, which makes cultural content more accessible, and opens new avenues for study in archives and museums [19]. Deep learning approaches have shown promise in pattern extraction and recognition in paintings and drawings, making

visual arts more accessible to wider audiences [20]. Computer vision techniques enable automated visual inspection of heritage structures, such as temple walls, stone pillars and sculptures [21]. Additionally, large multimodal models (LMM) can identify stone deterioration patterns in sculptures [22]. These tools and techniques facilitate the exploration and validation of primary data sources.

3.1 Textual manuscripts

India possesses one of the world's largest collections of manuscripts, covering diverse subjects and languages [23]. Textual records, including the Vedas, Puranas, Brahmanas, epics such as the Mahabharata and Ramayana, as well as Buddhist and Jain literature, provide detailed references to the culture, social structure, costumes and accessories of ancient eras [8]. However, manually analysing these texts can be challenging due to their complexity. Recognizing the importance of preserving this cultural heritage, the Indian government has initiated digital preservation efforts. The National Mission for Manuscripts has established resource and conservation centres, developing a National Database of Manuscripts [23]. Recent research highlights the potential of AI in decoding and exploring ancient manuscripts. Machine learning, natural language processing and pattern recognition techniques are applied to interpret ancient scripts and uncover linguistic phenomena [24]. Intelligent character recognition systems, enhanced by AI, address challenges in reading cursive characters from degraded manuscripts [25]. Deep learning methods, particularly generative adversarial networks (GANs), have shown promise in restoring ancient texts, with one study reporting 98% validation accuracy [26]. Generative AI techniques can facilitate intelligent research into ancient textual manuscripts through image processing, OCR and language model-based text mining and applications [27]. Convolutional neural networks have been employed for optical character recognition of Sanskrit manuscripts, demonstrating robustness to image quality variations [28]. Deep learning models,

such as MobileNet, ResNet and InceptionV3, have been used to recognize handwritten Tamil characters in palm-leaf manuscripts [29]. An end-to-end deep learning model using MobileNet for feature extraction and a bidirectional gated recurrent unit (BiGRU) for character recognition achieved 98.48% accuracy on Tamil handwritten documents [30]. A deep neural network called Ithaca achieved 62% accuracy in text restoration and significantly improved historians' performance from 25% to 72% when used collaboratively. The system also demonstrated high accuracy in geographical attribution (71%) and precise dating within 30 years of ground-truth ranges [31]. It can assist designers in the analysis of ancient inscriptions to extract shapes and motifs engraved on them. AI also can be leveraged to assemble fragments of ancient papyrus manuscripts [32]. AI and machine learning can assist in decoding unstructured knowledge embedded in cultural artifacts, encoding data in machine-readable systems and simulating the consequences of preserving or neglecting specific human experiences [33]. Machine learning approaches are reshaping the field of ancient language study, supporting tasks such as digitization, restoration, attribution, linguistic analysis, textual criticism, translation and decipherment [34]. These advancements show that using AI to decode and summarize old manuscripts can help extract and analyse specific details about the use of costumes and accessories from ancient times.

3.2 Sculptures and iconography

Ancient Indian fashion can be studied through sculptures and paintings recovered from historical sites, depicting the clothing patterns, accessories and hairstyles of different social groups [8]. Sculptures can be particularly useful in developing draping skills for fashion design education, as they provide fixed mannequins with clear details for students to study and replicate [35]. In 2023, Maitra analysed pictorial evidence from Jain paintings and combined it with foreign travellers' accounts and vernacular literature to provide insights into everyday life

during this period from medieval western India to reconstruct material culture, including clothing and ornaments [36]. Sculptures and paintings from ancient temples, caves and stupas visually document ancient Indian fashion, as sites such as Sanchi, Ajanta and Khajuraho depict elaborate clothing, jewellery and hairstyles. These artifacts directly depict how costumes and accessories were worn and their socio-cultural context. Although interpreting these visual details is challenging, computer vision algorithms and AI-powered image recognition tools using contrast limited adaptive histogram equalization (CLAHE) with CNN models can provide new possibilities when analysing sculptures with a maximum accuracy of 70.66% [37]. Recent advances in deep learning tools use computer vision algorithms to detect texture, colour and structural features in ancient art and paintings, making it easier to analyse these historical resources accurately [20, 38].

Interpreting these visual details can be challenging due to erosion, damage or stylistic abstraction in the artifacts. However, the above-mentioned tools and techniques help researchers analyse sculptures and paintings, identify patterns and reconstruct missing elements. Because these tools use computer vision algorithms to examine texture, colour and structural features in ancient artifacts, when these tools and techniques are combined with expertise in costume history and costume design, they improve the interpretation of collected data and support the desired outcomes.

3.3 *Archaeological findings*

Recent excavations at sites such as Mohenjo-Daro and Harappa provide evidence of the intricate ornament styles of the Indus Valley Tradition, showcasing skilled craftsmanship in creating jewellery from precious materials, stones, shells and faience, offering valuable insights into ancient fashion. These ornaments were also replicated in more accessible materials such as steatite and terracotta [38]. Various pieces of evidence of textiles, costumes and accessories can be found and studied from impressions

on pottery and corrosion products on metal artifacts excavated from archaeological sites in South Asia [39]. Excavations at Chanhu-daro reveal evidence of bead-making as a craft practiced in the Indus Valley Civilization [40]. The different types and styles of beads found in archaeological excavations across India provide insights into ancient fashion and adornment [41]. Archaeological excavations at Harappa provide evidence of specialized crafts such as shell working, ceramics and bead making from as early as 3300 BC [42]. Moreover, archaeological evidence also indicates the spread of cotton and flax textile production beyond the Harappan area in ancient India [43]. Textual data have also been analysed through text mining techniques such as natural language processing, while information extraction can be used to extract information from archaeological reports [44]. Archaeological excavations, findings and reports across India have unearthed remnants of textiles, jewellery, ad tools used in garment production. Such findings complement textual and visual sources, providing a holistic understanding of ancient clothing practices.

AI and machine learning technologies can revolutionize archaeological research by enabling advanced site analysis and artifact classification [45]. AI has advanced in natural language processing (NLP) and machine learning (ML), which are great at finding patterns, making predictions and organizing information [46]. It analyses large amounts of research data stored over the years through various survey reports, helps uncover new insights, and creates opportunities to use archived data for present and future studies. The processing of images using ML has been one of the most productive areas to date for archaeologists. The forms of images vary from photographs to stylized drawings of archaeological objects. Typically, ML has been used to identify “objects” within images and describe rock art and wall paintings [47]. ML can help reconstruct and restore fragmented 2D and 3D artifacts by matching their shapes, patterns and decorations, similar to solving a jigsaw puzzle [48-50]. ML has also been employed to

reconstruct fragmented artifacts, such as ostraca, using Siamese neural networks for pairwise matching with 96% accuracy [51]. Computational techniques are being explored for the virtual reconstruction of fragmented archaeological artifacts, including textiles, to assist in the time-consuming process of matching and assembling fragments, although it has limitations because of the unique challenges of archaeological textiles [52]. These studies explain that AI, ML and computational methods have the potential to analyse text, identify patterns and explore lost parts of fragmented artifacts.

4 AI applications in the restoration and recreation of ancient Indian costumes

Generative adversarial networks (GANs) have been used in clothing design to create new patterns and styles inspired by traditional elements, as seen in Dunhuang clothing from ancient Chinese culture [53]. GANs have been employed to digitally restore eroded temple sculptures, achieving an L1 loss of 0.29 after extensive training of the model for 7, 10, 000 iterations with the objective of rebuilding images of ancient temples as they were before being damaged by several invasions and climatic changes [54]. Mathematical biology techniques have been used to analyse and classify Indian costumes across different periods, revealing characteristic features that align with traditional concepts such as *prāna* and Yoga [55]. The AI-driven reconstruction of ancient clothing uses a generative adversarial algorithm to extract artistic elements from ancient artifacts and apply them to costume reconstruction and digitization, combining tradition with innovation. A dataset of sculptures, coins, paintings and iconography is created to train AI models, capturing details of costumes, jewellery and accessories for historical accuracy. The generated designs are then tested against DCGAN, fashion-GAN and other GAN-based clothing design models using inception scores and

human preference to ensure they are both aesthetically pleasing and culturally accurate. AI has proven useful in art restoration, successfully reconstructing missing parts of famous paintings and decoding ancient texts. Druzhinina highlights how it also helps us to collect data from ancient temple wall art and paintings [56]. ClothGAN uses generative adversarial networks and style transfer to create new patterns and styles for historical clothing out of data collected from historical resources [57]. An enhanced variational autoencoder method for dress style migration creates more refined synthetic images of traditional Indian styles [58]. Image inpainting can be improved by using larger datasets, deeper networks and powerful GPUs for faster learning. Adjusting network layers and incorporating mathematical models can increase accuracy. Future research may focus on developing new algorithms, drawing methods and better network designs to preserve cultural and artistic details in restored images [17]. These researchers highlight that AI is transforming clothing design by blending tradition with innovation. GANs and variational autoencoders aid in reconstructing and digitizing ancient fashion, ensuring historical accuracy. Improved datasets, deep learning models and 3D visualization enhance preservation efforts. Future research will refine algorithms, strengthening AI's role in safeguarding and modernizing cultural heritage.

4.1 *Machine learning in pattern recognition*

Pattern recognition techniques have been applied to Buddhist iconography for identifying period-specific features, analysing sculptures and recognizing hand gestures in religious artifacts [59]. Convolutional neural networks (CNNs) have proven effective in identifying artistic styles, motifs, and patterns in different fields, similar to the techniques used by art historians [60]. In historical image analysis, CNNs can classify art styles and organize artworks in chronological order without needing prior knowledge of art history [61]. Pranowo used CNNs to recognize Javanese batik patterns, attaining 90.14%

accuracy [62], while Kuntitan applied CNNs to classify motifs on Sukhothai ceramics, achieving 86.54% accuracy with a fine-tuned VGG16 model [63]. Similarly, CNNs have demonstrated exceptional accuracy in recognizing Indian textile patterns, with one study reaching 97.15% accuracy by combining CNN features with curvelet transforms [64]. The integration of ML algorithms in fashion design classification facilitates automated analysis and categorization based on different attributes, transforming the study of historical fashion. However, challenges such as data variability, interpretability and ethical concerns still exist [65]. Although there are some concerns, the researchers highlight the effectiveness of ML in studying historical fashion by automating pattern detection and classification. CNNs can recognize detailed surface patterns and silhouettes in sculptures and paintings. ML algorithms classify traditional Indian motifs such as paisleys, florals and geometric shapes, aiding in the accurate reconstruction of ancient garment designs.

4.2 *Natural language processing (NLP) for text analysis*

Recent research demonstrates the significant potential of NLP, making it an essential tool for analysing ancient Indian texts. By converting manuscripts into digital formats, NLP models can extract relevant information about clothing and accessories, such as descriptions of fabrics, dyeing techniques and weaving patterns. A novel system combining machine learning, image processing and NLP was proposed by [66] to convert Pali characters into understandable formats and decode the Pali Prakrit language, improving character recognition accuracy, and contributing to the preservation and study of this cultural heritage. [67] developed a question-answering model using BERT embeddings and gated recurrent unit (GRU) layers, achieving high accuracy rates on ancient Hindu scriptures, specifically the Atharv Ved, demonstrating a high accuracy rate of 94%. [68] introduced Vedalytics (Ved Analytics), an approach to retrieve the rules and concepts from

various ancient Indian scriptures, demonstrating improved specificity compared to generic language models. NLP strategies such as topic modelling and sentiment analysis have also been used to compare religious scriptures, revealing shared themes and differing perspectives across texts from Hinduism, Islam and Christianity [69]. Text classification and optical character recognition (OCR) are important areas of natural language processing for Indian languages, particularly Sanskrit. For the text classification of Indian language content, supervised learning algorithms such as Naive Bayes, Support Vector Machine, Artificial Neural Network and N-gram have shown good performance [70]. These studies highlight the effectiveness of NLP and AI in decoding, preserving and enhancing accessibility to ancient Indian texts, contributing to the understanding and conservation of cultural heritage.

4.3 *Computer vision for image analysis*

In the early days of advanced technology involvement, [71] used petrography and electron microprobe analysis to study the materials of Indian stone sculptures. This method examined artifacts from various regions and periods, such as Gandharan schist and Hoysala sculptures. Though limited, the study showed the potential for further research in identifying Indian stone artifacts. These studies contribute to the growing use of computational and analytical methods in this field. In a different approach, [72] developed a deep learning model to automatically recognize various features of Indian monuments from images, such as architectural style, time period and type. Their model was tested on a dataset of over 6,000 images from 117 monuments and achieved more than 80% accuracy. Similarly, [73] employed DCNN for monument classification, attaining 92.7% accuracy on a dataset of 100 monuments.

Recent advancements in computer vision have greatly contributed to studying traditional garments and iconography. Researchers have trained the advanced YOLOv8 model to identify traditional

costumes from different countries. For Indian saris, the model achieved an impressive 99% mean average precision [74]. In archaeology, machine learning and computer vision are helping to discover new details about Copper Age Iberian oculated idols, revealing artistic variations and regional differences that were previously unnoticed [75]. Deep feature fusion and content-based image retrieval systems such as InceptionV3 and InceptionResNetV2 models are being developed to assist designers in creating new motifs inspired by traditional patterns [76]. These tools have the potential to analyse sculptural and pictorial representations to identify draping styles, garment structures and jewellery designs. AI-powered systems can be successfully deployed to recreate digital models of ancient Indian attire by extracting details from temple sculptures.

4.4 3D modelling and virtual reconstruction

Virtual reconstruction is another significant application of AI in this field. AI technologies facilitate the creation of 3D models using textual descriptions, photographs, paintings and archaeological data, providing immersive insights into historical artifacts and costumes. [77,78]. AI has made remarkable progress in generating images from text descriptions and reference images. State-of-the-art AI tools, such as DALL-E 2, can produce high-quality images from text prompts and use a reference image to guide the process [79]. Even for 2D restoration, a framework combining neural style transfer, U-Net and Partial Convolution networks have been developed to repair damaged regions in ancient Indian murals [80]. This suggests that when AI image generation technology matures in the next few years, it could become a valuable tool for creating the virtual reconstructions of artifacts in the future. AI technologies enable the virtual reconstruction of ancient costumes and accessories, offering immersive insights into cultural heritage. These technologies support the cataloguing of cultural collections, the restoration of artworks and the preservation of intangible heritage [81]. Despite its limitations, AI-driven integration systems

have the transformative potential to digitally recreate and restore ancient costumes, offering a unique perspective to explore and share the rich history of costumes with future generations [82]. Recent research highlights the expanding role of AI in virtual reconstruction and restoration by integrating data from textual, visual and archaeological sources. By leveraging AI, researchers can generate 3D models of ancient costumes and accessories, while emphasizing ethical considerations such as data privacy, cultural authenticity and community involvement. These 3D models offer immersive insights into how garments were worn and their cultural significance, enhancing museums and educational platforms to bring ancient Indian fashion to life.

5 Challenges in AI-based restoration efforts

Even though AI has potential, using it to recreate and restore ancient Indian costumes, textiles and accessories has many challenges. The cultural dependencies embedded in AI technologies, predominantly developed in a handful of countries, can lead to incongruencies when applied globally [83]. The development of a culturally sensitive AI model, trained in regional aspects, will be required. Generic algorithms may fail to capture the nuances of regional variations and symbolic meanings inherent in Indian costume analysis. It is important to design AI systems that include the historical, cultural and social backgrounds of ancient India for accurate restoration.

Furthermore, general puzzle-solving algorithms, especially those based on deep learning, have shown promising performance on artificially fragmented natural images. However, they face some challenges when used for studying archaeological textiles [84]. When dealing with highly incomplete pieces, a hybrid human-computer approach is often necessary. This method combines expert knowledge with computational solutions to achieve credible

restorations, as demonstrated in the reconstruction of Roman sculptures [85]. It shows that interpreting incomplete or degraded data poses technological constraints. Artifacts that are partially damaged or eroded require advanced algorithms capable of reconstructing missing elements without distorting historical accuracy.

5.1 Limitations of AI in Interpreting cultural nuance

The application of AI in historical costume restoration is accompanied by notable limitations, particularly in addressing cultural nuance and contextual integrity. AI-generated reconstructions, when reliant solely on data-driven algorithms, are susceptible to inaccuracies that may distort the original intent of traditional attire. These models often fail to account for the socio-cultural, religious or ceremonial significance embedded in garments, especially when training data lacks representational diversity or is devoid of ethnographic context [83]. These limitations lead to the oversimplified outcome where complex draping techniques, symbolic textile patterns and region-specific stylistic variations are often distilled into visually coherent but historically inaccurate representations, even if they may be aesthetically convincing. This result will interpret the cultural identity.

5.2 Data gaps in training AI models

One of the most significant obstacles in AI-assisted historical costume restoration is the availability and quality of primary data. Many traditional sources from ancient manuscripts, sculptures, paintings and textile fragments are either degraded, inaccessible or not digitally accessible. Additionally, cultural and linguistic diversity in the same era of ancient India makes it harder to understand correctly in the case of the detailed information related to costume analysis. Inadequate data volume or resolution limits the robustness of training datasets, which directly impacts the accuracy and reliability of AI outputs. Moreover, historical records often lack standardized

documentation, leading to inconsistencies in metadata, terminology and visual representation across sources. These data gaps introduce biases and errors in model training, where the algorithm overfits to dominant styles or well-preserved artifacts, while underrepresenting regional or marginalized traditions. As a result, reconstructions may reflect only a narrow slice of cultural history, distorting the broader narrative. In the case of rare fragmented datasets, AI may generate an outcome based on statistical inference rather than historical accuracy, which can compromise the authenticity of the restoration [86].

6 Conclusion

The enduring value of India's ancient costumes and textiles, with the intricate techniques of weaving, dyeing, printing and embroidery, reflects the craftsmanship of earlier generations and serves as a testament to the diversity of India's textile heritage [87]. These studies find that collaborative efforts between AI experts, historians and designers are crucial to addressing these challenges effectively when making efforts to recreate and restore historical costumes and accessories with precision. China's digitization of Dunhuang textiles has leveraged GANs and deep learning to reconstruct traditional garments with high aesthetic fidelity [54], while European efforts in Byzantine mosaic restoration employ multimodal AI systems that integrate textual, visual and archaeological data for contextual accuracy. Even initiatives such as the restoration of Shakti sculptures from the Paramara period [15] and Indus Valley ornament styles [40] highlight how computer vision and deep learning tools are being applied to study the intricate designs and motifs found in archaeological and sculptural artifacts. For instance, deep learning models such as CLAHE-enhanced CNNs have been used to classify and extract features from Indian sculptures with over 70% accuracy [39], aiding in the interpretation of garment structure and jewellery design.

Additionally, AI models have been deployed to decode palm-leaf manuscripts and Sanskrit inscrip-

tions [30, 32] helping reconstruct cultural knowledge surrounding ancient clothing practices, fabric usage and textile production methods. These efforts reflect an emerging trend in India that integrates natural language processing, computer vision and machine learning to recover fragmented historical narratives through primary sources. These studies contrasted with traditional restoration techniques such as the manual decoding of scripts, artisan consultation, textile analysis, manual sketching and artisan-led reconstructions, and offer deeper cultural understanding and material sensitivity but are often time-consuming and resource-intensive. Thus, by integrating AI-driven methodologies with traditional research practices, it is possible to achieve more accurate and comprehensive results. Combining AI's computational power with traditional expertise, a hybrid model emerges as the most viable approach. Such integration ensures the technical precision, cultural authenticity and ethical responsibility necessary in preserving intangible heritage.

Future research should focus on expanding the digitization of primary data sources and developing region-specific AI models. Collaborative projects between cultural heritage institutions, universities and technology companies can accelerate advancements in this field. Additionally, incorporating augmented reality (AR) and virtual reality (VR) technologies can enhance the visualization and accessibility of ancient Indian fashion for educational and cultural purposes. This study emphasizes the importance of balancing technological innovation with ethical considerations, advocating for ongoing dialogue among stakeholders to ensure AI in fashion evolves responsibly, inclusively and ethically, ultimately fostering a harmonious coexistence between technology and human creativity.

Data availability statement: The datasets generated and/or analyzed during the current study are since October 13, 2025 available in the Zenodo repository: <https://doi.org/10.5281/zenodo.17338847>.

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Impulse Buying Behaviour in Apparel Retail: Exploring the Role of Store Atmosphere and Situational Factors

Impulzivno potrošniško vedenje v prodaji oblačil: raziskovanje vloge vzdušja v trgovini in situacijskih dejavnikov

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Abstract

This study investigates the impact of store atmosphere and situational factors on impulse buying behaviour among apparel consumers, with a particular focus on the mediating role of situational factors. A quantitative research approach was employed, utilising partial least squares structural equation modelling (PLS-SEM) to provide comprehensive insights. Data were collected through convenience sampling from 501 apparel consumers in India. The research examines the influence of store atmospheric elements, including store ambiance, design, social factors and clothing touch, together with situational factors such as promotional offers, time availability, money availability, mood and the presence of others. The findings reveal a complex interaction between store atmosphere, situational factors and impulse buying behaviour. Specifically, store ambiance, design and key situational factors emerge as significant drivers of impulsive purchases. By incorporating situational factors as mediators, this study offers a nuanced research framework tailored to the apparel retail sector. The insights gained provide valuable implications for retailers, who can strategically enhance store atmosphere and situational conditions to effectively stimulate impulse buying behaviour among apparel consumers.

Keywords: store atmosphere, situational factors, apparel consumers, impulse buying behaviour

Izvleček

Članek preučuje vpliv vzdušja v trgovini in situacijskih dejavnikov na impulzivno nakupovalno vedenje kupcev oblačil, s posebnim poudarkom na posredniški vlogi situacijskih dejavnikov. Pri raziskavi smo uporabili kvantitativni pristop, za celovito analizo pa metodo delnih najmanjših kvadratov PLS-SEM. Podatki so bili zbrani s priložnostnim vzorčenjem, in sicer med 501 kupcem oblačil v Indiji. Raziskava preučuje vpliv trgovinskega vzdušja, ki vključuje ambient, oblikovanje prostora, socialne dejavnike in možnost dotikanja oblačil, skupaj s situacijskimi dejavniki, kot so promocijske ponudbe, koliko časa in denarja je na voljo, razpoložanje ter prisotnost drugih oseb. Ugotovitve razkrivajo zapleteno medsebojno delovanje med trgovinskim vzdušjem, situacijskimi dejavniki in impulzivnim



nakupovalnim vedenjem. Zlasti ambient trgovine, oblikovanje in ključni situacijski dejavniki so se pokazali kot pomembni spodbujevalci impulzivnih nakupov. Z vključitvijo situacijskih dejavnikov kot posredniških spremenljivk ponuja raziskava izpopolnjen raziskovalni okvir, prilagojen maloprodajnemu sektorju oblačil. Ugotovitve imajo lahko pomembno praktično vrednost za prodajalce, ki lahko z načrtnim oblikovanjem trgovinskega vzdušja in situacijskih pogojev učinkoviteje spodbujajo impulzivno potrošniško vedenje.

Ključne besede: vzdušje v trgovini, situacijski dejavniki, kupci oblačil, impulzivno potrošniško vedenje

1 Introduction

In the fast-paced world of retail, where competition is fierce and consumer preferences evolve rapidly, understanding the drivers behind impulse buying behaviour is crucial for businesses to remain competitive and thrive. Among the multitude of factors that influence consumer decision-making, two key elements stand out: store atmosphere and situational factors [1]. These factors not only shape the overall shopping experience but also play a pivotal role in triggering impulsive purchases, especially within the apparel product category [2]. Impulse buying, characterized by spontaneous and unplanned purchases, holds considerable implications for retailers seeking to capitalize on consumers' in-the-moment decisions [3]. While extensive research has delved into various aspects of consumer behaviour, the interplay between store atmosphere, situational factors and impulse buying remains a nuanced and evolving area of study, especially within the apparel sector [4]. Impulse buying plays a significant role in apparel shopping and holds strategic importance. Impulse purchases can account for a large portion of retail sales, especially in fashion where emotional appeal and visual aesthetics heavily influence buying behaviour [4,5]. Retailers use visual merchandising, strategic product placement (near checkout or on home pages) and limited time offers to trigger impulsive decisions [6]. Impulse buying is linked to emotions, mood and self-expression. Understanding it helps brands tailor marketing strategies that tap into consumers' desires for instant gratification, novelty or even retail therapy [5, 7].

The concept of store atmosphere encompasses the tangible and intangible elements of the retail environment, including store ambiance, design, social factors and clothing touch. These atmospheric factors exert a profound influence on consumers' emotions, perceptions and behaviours, thereby shaping their shopping experiences and purchase decisions [5]. Moreover, situational factors, such as mood, time pressure, money constraints, promotional offers and the presence of others during shopping, play a pivotal role in triggering impulsive buying tendencies [6,7]. Consumers' psychological states and external stimuli interact dynamically with the store environment, prompting spur-of-the-moment purchases that may deviate from their planned shopping intentions [8].

The store atmosphere encompasses the sensory elements and overall ambiance of the retail environment. From the visual appeal of store displays to the aroma wafting through the air, every aspect of the store atmosphere contributes to the overall mood and atmosphere experienced by shoppers [9]. Research has shown that certain atmospheric cues, such as lighting, music, scent and spatial layout, can significantly influence consumers' emotions, perceptions and purchasing behavior [10]. Retailers often strategically design their stores to evoke specific emotions and enhance the overall shopping experience, to drive sales and foster customer satisfaction. In addition to store atmosphere, situational factors play a crucial role in shaping impulsive buying behaviour [11]. These situational cues include factors

such as mood, time pressure, money constraints, promotional offers and the social presence of others. For instance, a shopper may be more inclined to make impulsive purchases when feeling happy or excited, or when faced with time constraints and the fear of missing out on a deal. Similarly, the presence of friends or peers can exert social pressure and influence individuals' purchase decisions [12–14].

Against this backdrop, this research aims to delve deeper into the interplay between store atmosphere, situational factors and impulse buying behaviour in the context of apparel consumption. By examining how specific atmospheric cues and situational elements influence consumers' propensity to make impulsive purchases, this study seeks to provide valuable insights for retailers looking to optimize their strategies and create compelling shopping experiences. Through a comprehensive analysis utilizing quantitative surveys, this research aims to uncover the underlying mechanisms driving impulse buying behaviour and offer practical recommendations for retailers to enhance their competitive edge on the apparel market.

Through a quantitative method approach integrating quantitative surveys, this study seeks to capture the multifaceted dimensions of consumer behaviour and offer nuanced perspectives on the impact of store environment and situational factors on impulsive buying tendencies. By shedding light on these intricate dynamics, retailers can refine their approaches to create immersive retail experiences that resonate with the evolving needs and preferences of apparel consumers.

1.1 Store atmosphere and impulse buying behaviour

Impulse buying is a spontaneous, unplanned decision to purchase, driven more by affective reactions than cognitive deliberation. Conceptually, it involves a complex interplay of emotional arousal, diminished self-control and situational cues. Research suggests [11–13], that factors such as hedonic motivation, instant gratification and even self-identity reinforce-

ment contributes to impulse buying behaviour. Store atmosphere refers to the physical and sensory elements of a retail environment that influence customer perceptions and behaviours [14]. Store atmosphere plays a crucial role in shaping consumers' emotions, perceptions and behaviours, ultimately influencing their impulse buying behaviours, particularly in the apparel category [12, 15]. The ambiance, layout, music, lighting and overall sensory experience of a store collectively contribute to its atmosphere, creating a distinct environment that can either encourage or deter impulse purchases [16–18]. Firstly, the visual appeal of a store, including its layout, product displays and decor, sets the stage for consumers' shopping experiences [19]. A well-designed store layout can guide consumers through the space, drawing their attention to specific merchandise and enticing them to explore further [20]. Eye-catching displays of apparel items, arranged in aesthetically pleasing configurations, can evoke desire and stimulate impulse buying more [21]. For example, strategically placed mannequins showcasing trendy outfits or visually appealing product arrangements can trigger impulse purchases by creating a sense of urgency and desire to emulate the displayed styles. The colour scheme in a store can elicit various emotional responses and attract customers' attention [22, 23]. Consumers can be stimulated by colour and put in a buying frame of mind [5]. Utilizing warm colours such as yellow and red on the packaging, and cool and relaxing colours such as violet or blue on the background walls of the store can catch the customer's attention [24]. Warm colours in a retail outlet attract customers, whereas cool colours generate favourable responses among customers, affecting customer behaviour when purchasing [25]. Moreover, the use of lighting can significantly impact consumers' perceptions and behaviours within a store. Lighting influences mood and ambiance, with bright, well-lit spaces often associated with positivity and energy, while dimmer lighting can create a more intimate and relaxed atmosphere [26]. Retailers can leverage lighting techniques to enhance the visual appeal of apparel items,

highlight specific areas or promotions, and evoke desired emotions conducive to impulse buying [27]. For instance, soft, flattering lighting in fitting rooms can make shoppers feel more confident and inclined to make impulsive clothing purchases. Additionally, the auditory elements of the store atmosphere, such as background music, contribute to the overall sensory experience and can influence consumers' emotional states and purchasing behaviour [28]. Upbeat music with a fast tempo has been found to increase arousal and excitement levels, potentially leading to heightened impulse-buying tendencies. Conversely, slow-tempo music or calming melodies can create a more relaxed shopping environment, which may deter impulsive purchases [29, 30]. Retailers can strategically select music genres and playlists to align with their target demographic and desired shopping atmosphere, thereby influencing consumers' moods and propensity for impulse buying [31]. Furthermore, olfactory cues, such as ambient scents, can evoke powerful emotional responses and influence consumers' perceptions of a store's atmosphere [30, 32]. Pleasant fragrances, carefully chosen to complement the brand image and enhance the shopping experience, can evoke positive emotions and enhance consumers' moods, thereby increasing their receptivity to impulse purchases [33]. For example, the subtle scent of fresh linen or floral notes can evoke feelings of freshness and luxury, creating a sensory-rich environment conducive to impulse buying in the apparel sector [34].

The interaction between salespersons and shoppers can significantly influence impulse buying behaviour in apparel stores [35]. A friendly, knowledgeable and attentive salesperson can create a positive shopping experience, build rapport with customers and subtly encourage impulse purchases [36]. Salespersons who engage in suggestive selling techniques, such as recommending complementary items or highlighting limited time offers, can prompt shoppers to make spontaneous purchases they had not initially planned [37]. Moreover, salespersons who provide personalized assistance, offer styling advice

or express enthusiasm for clothing items can enhance shoppers' emotional engagement and increase the likelihood of impulse buying [38]. On the other hand, the presence of a crowd in an apparel store can also impact impulse buying behaviour. Research suggests that crowded environments can create a sense of urgency and excitement, prompting shoppers to feel a fear of missing out (FOMO) on desirable items or limited-time promotions [39]. As a result, shoppers may be more inclined to make impulsive purchases to avoid regret or competition from other customers. Additionally, the social influence of a crowd can lead to conformity behaviour, where shoppers are influenced by the purchasing decisions of others, further amplifying impulse buying tendencies [40–42].

The tactile experience of touching clothing items can play a significant role in triggering impulse buying behaviour. Research has shown that tactile sensations can evoke emotional responses and influence consumers' perceptions of product quality and desirability [43]. In apparel stores, allowing customers to physically interact with garments by touching fabrics, trying on clothing items or feeling textures can enhance their sensory experience and stimulate impulse purchases [44]. The pleasurable sensation of touching soft fabrics or admiring intricate details can create a sense of immediate gratification, prompting shoppers to make impulsive buying decisions [45, 46].

1.2 Situational factors and impulse buying behaviour

Situational factors play a crucial role in influencing impulse buying behaviour in the context of the apparel product category. Numerous situational factors, such as promotional offers, availability of time, money availability, consumer mood and the presence of others during shopping, can impact impulse buying behaviour. Promotional offers such as discounts, sales and limited-time promotions create a sense of urgency and scarcity, prompting shoppers to make impulsive purchases [47]. When consumers perceive a good deal or perceive potential savings, they may feel compelled to capitalize on the

Table 1: Theoretical backing summary: impulse buying behaviour in apparel shopping

Conceptual link	Supported by	Key insights
Store atmosphere: Emotional/Affective states	[30, 58, 59, 60, 61, 65]	Store ambiance, layout, scent, lighting and music trigger emotional responses (pleasure, arousal), influencing consumers' psychological readiness to buy.
Clothing touch: Impulse buying	[61, 62]	Tactile interaction with products, especially in apparel, heightens attachment and desire, leading to impulsive purchases.
Store atmosphere: Situational perception	[59, 64]	A well-designed atmosphere reframes the shopping context (e.g., urgency, hedonic value), modifying situational interpretations like mood, time pressure and social cues.
Situational factors: Impulse buying	[63, 64, 66, 73]	Time availability, presence of others, promotions and current mood have strong direct effects on unplanned purchasing behaviour.
Store atmosphere: Situational factors (Mediator)	[59, 60, 62, 65]	Store design and sensory elements shape how situational variables (e.g. perceived urgency, money availability) are experienced.
Mood as a mediator	[30, 64]	Positive emotional states induced by the store environment increase consumers' impulsivity and willingness to indulge.
Presence of promotions: Impulse buying	[63, 66, 73, 74]	Discounts and limited time offer create urgency and justify spontaneous purchases.
S-O-R model justification	[58, 65, 67]	The S-O-R model frames store atmosphere as stimulus (S), emotional/cognitive state as organism (O) and impulse buying as response (R).

opportunity, leading to spontaneous buying decisions, especially for apparel items they may not have initially planned to purchase [10]. Time constraints influence impulse buying behaviour in apparel stores [48]. When shoppers are pressed for time or have limited availability, they may be more inclined to make quick, impulsive purchases rather than engaging in extensive deliberation or comparison shopping [49–51]. In such situations, consumers may prioritize convenience and immediacy, opting for impulse buys rather than spending time searching for the perfect item [52, 53].

The perceived availability of money impacts impulse buying behaviour for apparel [53]. When consumers feel financially secure or have disposable income readily available, they may be more willing to indulge in spontaneous purchases, especially if they perceive the item as affordable or within their budget [11]. Conversely, financial constraints or concerns about overspending may curb impulse buying tendencies, as consumers prioritize financial prudence and budgetary constraints [54]. Consumer mood can significantly influence impulse buying behaviour in apparel stores. Positive emotions such as happiness and excitement can lower inhibitions

and increase impulsivity, leading consumers to make spontaneous purchases to enhance their mood or reward themselves [55]. Conversely, negative emotions such as stress, sadness or boredom may also trigger impulse buying as a coping mechanism or to alleviate negative feelings through retail therapy [37, 56]. The presence of friends, family members or peers during shopping can influence impulse buying behaviour in apparel stores. Social interactions and peer pressure can impact consumers' purchase decisions, as individuals may feel compelled to conform to group norms or seek approval from others [57, 58]. Additionally, shopping with companions can enhance the enjoyment of the shopping experience and increase the likelihood of impulse purchases through social influence and shared experiences.

1.3 Summary of theoretical backing (impulse buying behaviour for apparel)

Table 1 summarizes the theoretical contributions from key studies supporting the conceptual model linking store atmosphere, situational factors and impulse buying behaviour in apparel shopping. The framework draws from the S-O-R model and

emphasizes emotional and contextual mediators. Table 1 provides an in-depth understanding of the conceptual link between store atmosphere, situational factors and impulse buying behaviour for apparel.

1.4 Proposed research framework

The proposed research framework, as seen in Figure 1: Proposed research framework, was developed through a comprehensive literature review on store atmosphere and situational variables affecting impulse buying in apparel consumers. The study proposes that situational factors mediate the relationship between store atmosphere and impulse buying. Elements of store atmosphere and situational factors,

including promotional offers, time, money, mood and the presence of others, were identified and used to build the research framework. Hypotheses were then developed to assess impulse buying behaviour in apparel consumers.

H1: There is a positive relationship between store atmosphere and impulse buying behaviour for apparel.

H2: There is a positive relationship between store atmosphere and situational factors.

H3: There is a positive relationship between situational factors and impulse buying behaviour for apparel.

H4: There is a positive relationship between store atmosphere and impulse purchasing behaviour based on situational factors as a mediator.

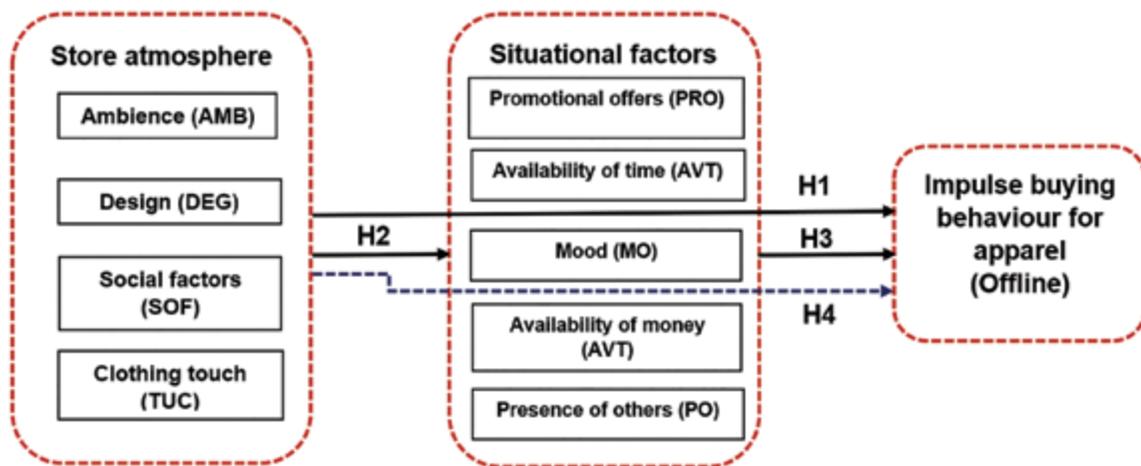


Figure 1: Proposed research framework

2 Methodology

This study used a quantitative method to assess the relationship between store atmosphere, situational factors and impulse buying behaviour in apparel consumers. A non-probability (convenience) sampling technique was employed for this study. The respondents were apparel shoppers in retail stores in India. India has heterogeneous consumers: urban/rural, income groups, cultures, etc. Convenience sampling was chosen due to its practical advantages in accessing a large and diverse pool of participants within a limited timeframe and resource constraints. India serves as an ideal context for examining im-

pulse buying behaviour in apparel shopping due to its dynamic retail environment, rapid urbanization and growing middle-class consumer base. The Indian apparel market is characterized by a blend of traditional and modern retail formats, increasing exposure to global fashion trends, and a strong influence of in-store environments and promotions on consumer behaviour. Given the large and diverse nature of the Indian consumer market, collecting 501 valid responses provides a robust dataset that captures variability across demographics such as age, gender, income levels and shopping habits. Structural equation modelling (PLS-SEM) was used to analyse the associations between the variables. A

total of 501 valid responses were gathered, which exceeds the minimum sample size requirements for structural equation modelling (SEM).

2.1 Sample size determination

Sample size determination is a significant challenge when SEM is preferred for data analysis [58]. The “10-times rule” approach is a popular minimum sample size estimation method in SEM. Researchers have advised that a study utilizing SEM requires a sample size of 200 or that five to 10 samples per element would be adequate [72, 75, 76]. However, SEM researchers have often employed sample sizes ranging from 300 to 400. Therefore, 490 responses were targeted for this study. A total of 650 questionnaires were distributed with the aim of receiving back 490 for further data analysis. A total of 550 responses were received. After data cleaning, 501 apparel consumer responses were deemed valid for further data analysis.

2.2 Questionnaire development

A structured questionnaire was utilized in this study to collect individual responses. The questionnaire in this study was carefully developed to improve the participants’ response rate. Thus, the study makes it as simple and visually appealing as possible. To assess the impact of apparel customers’ impulsive purchasing behaviour, the study’s questionnaire was split into two sections, as follows:

Section 1: This section included multiple choice questions about impulse buying, store atmospheric cues and situational factors.

Section 2: This section included a question related to the demographic profile of apparel consumers.

Section 1 was developed to determine if respondents’ recent purchases were impulsive. A five-point Likert (strongly agree-disagree) scale that contained and modified three items was used in this study to examine the urge to buy apparel products impulsively. Sixteen items in four dimensions of the apparel retail store were examined to evaluate the

store atmosphere. Each retail store aspect (including ambience factors, design variables, social factors and clothing touch) had four items used to measure the impulse purchasing behaviour of apparel consumers. A Likert scale with five points ranging from strongly disagreeing to strongly agreeing was utilized to assess four items evaluating ambience variables, and for design elements, social factors and clothing touch. Similarly, a total of 20 items in five dimensions of situational factors were assessed. Each measurement of situational factors (including mood, money availability, time availability, promotional offers and the presence of others) had four items that were utilized to evaluate impulse buying for apparel. In addition, four items were measured using a scale developed and modified by [61] to assess the impact of the mood of apparel consumers. In addition, questions about money and time availability were adopted from the study of [62]. Further, a scale was used to assess how much purchasers are influenced by others during apparel shopping. Similarly, four items related to promotional offers were considered in the study [63].

2.3 Reliability and validity analysis

Reliability and validity have been identified as crucial elements of any quantitative research in measuring research quality. In this study, reliability was first evaluated using Cronbach’s alpha, and then by composite reliability (CR) and average variance extracted (AVE). The threshold values for alpha, CR and AVE are 0.70 (both alpha and CR) and above, and 0.50 and above for AVE [77–79]. Table 2 presents all variables of latent constructs that are highly reliable. Furthermore, convergent validity and discriminant validity were used to evaluate the validity of the quantitative data [71, 77] and to verify scale validity using the heterotrait-monotrait ratio (HTMT). The preferred value of HTMT should be less than 1 [78]. Table 3 indicates the values of HTMT were between 0.50 to 0.82, which was acceptable for measuring discriminant validity.

Table 2: Factors of store atmosphere, situational factors and impulse buying behaviour

Constructs		Factor loadings	CR ^{a)}	AVE ^{b)}	Alpha
Ambiance (AMB)	AMB2	0.688	0.89	0.54	0.90
	AMB3	0.692			
	AMB4	0.663			
Design (DEG)	DEG1	0.665	0.92	0.51	0.94
	DEG2	0.701			
	DEG3	0.748			
	DEG4	0.669			
Social factors (SOF)	SOF1	0.688	0.85	0.53	0.85
	SOF2	0.687			
Clothing touch (TUC)	TUC1	0.672	0.93	0.52	0.95
	TUC2	0.683			
	TUC3	0.692			
Promotional offers (PO)	PO1	0.738	0.86	0.57	0.88
	PO2	0.687			
	PO3	0.737			
	PO4	0.689			
Availability of time (AVT)	AVT1	0.667	0.89	0.51	0.91
	AVT3	0.731			
	AVT4	0.686			
Availability of money (AVM)	AVM1	0.679	0.94	0.53	0.96
	AVM2	0.713			
	AVM3	0.639			
	AVM4	0.736			
Presence of others (PO)	PRO1	0.699	0.92	0.62	0.87
	PRO3	0.663			
	PRO4	0.67			
Mood (MO)	MO1	0.782	0.90	0.52	0.89
	MO3	0.668			
Impulse buying behaviour for apparel (IMPB)	IMPB1	0.692	0.79	0.50	0.75
	IMPB2	0.701			
	IMPB3	0.683			

^{a)} Composite reliability, ^{b)} Average variance extracted

Table 3: Discriminant validity analysis

Latent variables	IMPB ^{a)}	S.F. ^{b)}	S.A. ^{c)}
Impulse buying behaviour	--	--	--
Situational factors	0.53	--	--
Store atmosphere	0.50	0.75	--

^{a)} Impulse buying behaviour, ^{b)} Situational factors, ^{c)} Store atmosphere

2.4 Common method bias (CMB)

In this study, Harman's single factor score was employed to assess the common method bias. A single factor's total variation has been suggested to be less than 50%. If the number is less than 50%, it means that CMB has no effect on the responses and, thus, the study's findings. Table 4 shows that the value of total variance (16.736) is less than 50%, which indicates that CMB has no effect on the data. Thus, CMB was not a problem in this investigation. To further assess the potential impact of common method bias (CMB), the marker variable technique was applied. The correlations between the marker variable and the main study constructs (store atmosphere, situational factors, and impulse buying behaviour) were all non-significant ($p > 0.05$). This suggests that common method variance is unlikely to significantly bias the results. The marker variable showed weak correlations with all main constructs (ranging from $r = 0.04$ to $r = 0.06$), while none were statistically significant ($p > 0.05$). This indicates minimal risk of common method bias in this study.

Table 4: Common method bias

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	Percentage of variance (%)	Cumulative (%)	Total	Percentage of variance (%)	Cumulative (%)
1	9.540	16.736	16.736	9.540	16.736	16.736
2	5.007	8.785	25.521			

2.5 Correlation analysis

To assess the correlation between latent constructs, the Pearson correlation test was used. The acceptable

range of coefficient correlation (r) lies between -1 to +1. The r values between 0.36 to 0.67 are considered a moderate association among constructs [80, 81]. The

values for coefficient correlation for situational factors ($r = 0.52$) and store atmosphere ($r = 0.50$) are given in Table 5. There is no multicollinearity problem in the data, as it is suitable for further SEM analysis.

Table 5: Correlation analysis

Latent constructs	IMPB ^{a)}	S.F. ^{b)}	S.A. ^{c)}
Impulse buying behaviour	1.00	0.52	0.50
Situational factors	0.52	1.00	0.75
Store atmosphere	0.50	0.75	1.00

^{a)} Impulse buying behaviour, ^{b)} Situational factors, ^{c)} Store atmosphere

3 Results and discussion

3.1 Demographic profile of the respondents

Table 6 presents the descriptive statistics of the respondents' demographic profile. Most respondents were female (56.08%) and male (43.92%). The majority (50.30%) were aged 18–25, with 30.73% aged 25–35, 14.17% aged 35–45 and 4.79% over 45. In terms of family income, 28.14% earned 487–974 EUR (50,000–100,000 INR) and 25.55% earned above 4,870 EUR (above 500,000 INR). About 76% had graduation (46.91%) or post-graduation (29.14%) education levels.

3.2 Structural model evaluation

To evaluate the links between latent constructs, the PLS-SEM method was used for this study. SEM is a combination of factor analysis and path analysis. SEM analysis has enabled route analytical modelling on latent variables using the SMART-PLS tool. CFA is a part of the measurement model of PLS-SEM, which assesses the outer loadings, composite reliability, convergent validity, discriminant validity and AVE. Outer loadings are the regression weights with

Table 6: Descriptive analysis (demographic profile of respondents)

Measure	Items	Frequency	Percentage
Gender	Male	220	43.92
	Female	281	56.08
Age	18–25 years	252	50.30
	26–35 years	154	30.73
	36–45 years	71	14.17
	> 45 years	24	4.79
Monthly family income (INR ^{a)})	< 50.000	78	15.57
	50.000–100.000	141	28.14
	100.000–200.000	84	16.77
	200.00–500.000	70	13.97
	> 500.000	128	25.55
Education level	Intermediate	70	13.97
	Graduation	234	46.91
	Post-graduation	146	29.14
	Above post-graduation	51	9.98

^{a)} 1 INR = 0.0098 EUR

recommended benchmarks of 0.6 and 0.7 [68–70]. The foremost factor structure revealed four constructs from store atmosphere (AMB1, SOF3, SOF4, TUC4), four factors from situational factors (AVT2, PRO2, MO2, MO4) and one factor (IMPB4) from impulse buying behaviour are eliminated from the model as its factor loading is lower than the expected value 0.6 (see Table 2).

The outer model, or structural model, assesses path coefficients to determine R^2 values and significance levels using t-statistics and p-values. R^2 is crucial for evaluating the model. In the model (see Figure 2: Structural model), store atmosphere is the independent variable, situational factors are mediators and impulse buying behaviour is the dependent variable. Thus, situational factors mediate the relationship between store atmosphere and impulse buying behaviour for apparel consumers.

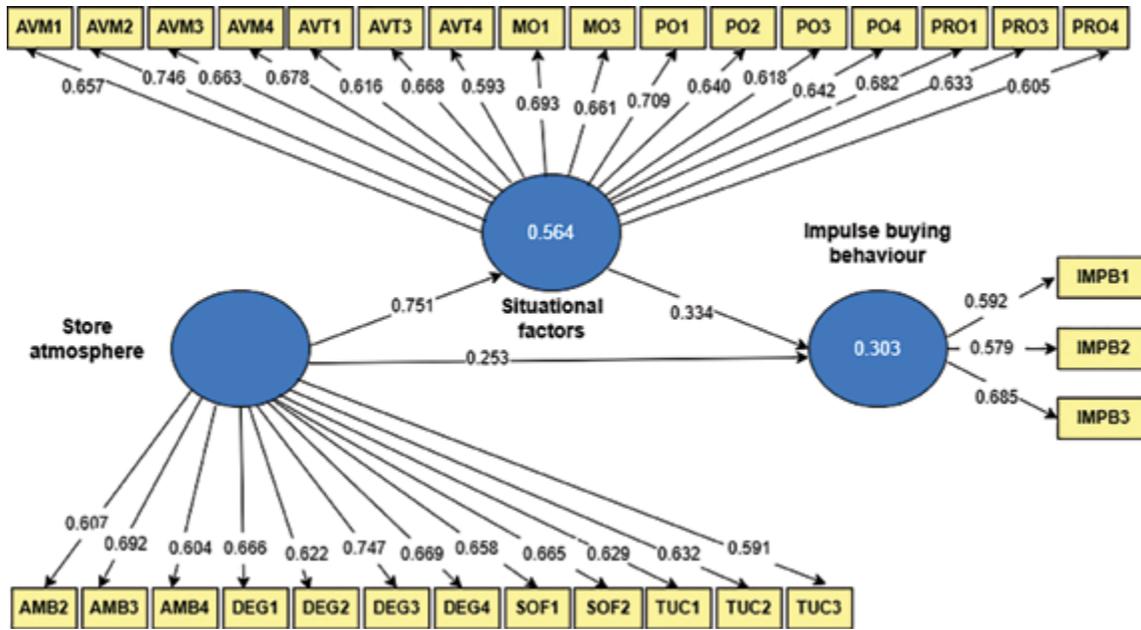


Figure 2: Structural model

It is predicted that the R^2 parameters will be met with a minimum of 10% accuracy [81]. Table 7 shows that 30.3% of the variance is explained by impulse buying behaviour, whereas 56.4% is explained by situational factors in the model. The standard was set to 0.02 for weak, 0.13 for moderate and 0.26 for the strong coefficient of determination [82]. It was found that impulse buying behaviour and situational factors have a strong effect. Predictive relevance (Q^2) was also examined along with the R^2 as a measure of accuracy determined through the blindfolding procedure. A Q^2 value above zero shows predictive relevance. However, in Table 7, Q^2 for impulse buying behaviour is 0.102, while it is 0.272 for situational factors, indicating a high degree of predictive relevance [83]. The model's goodness of fit was assessed through SRMR (standardized root mean square residual) and the normed fit index (NFI). The acceptable value of SRMR must be less than 0.10 (J. F. Hair, Henseler, et al., 2014), while the acceptable value of NFI must be close to 1 [84–86]. Table 8 shows the value of SRMR was 0.07 and NFI was 0.7, indicating the model is a good fit.

Table 7: Analysis of coefficient of determination

Latent Variables	R^2	R^2 adjusted	Q^2 ^{b)}
Impulse buying behaviour	0.303	0.313	0.102
Situational factors	0.564	0.568	0.272

^{a)} Coefficient of determination, ^{b)} Predictive relevance

Table 8: Analysis of goodness of fit

Model fit	Estimated model
SRMR	0.07
NFI	0.70

3.3 Hypothesis testing

The PLS-SEM model assesses the relationships between latent constructs by analysing path coefficients and significance levels. Table 9 presents the results of path coefficients, t-statistics and p-values. The findings reveal that store atmosphere significantly influences impulse buying behaviour for apparel, contributing 25% to the direct effect on impulse buying (see Figure 3). Further, store atmosphere has a positive and significant relationship with impulse buying behaviour as its t-statistics is 5.18 > 1.96,

while the p-value is 0.00, which is less than 0.05. This indicates that the retail atmosphere is a crucial determinant of impulsive buying for apparel. Therefore, hypothesis H1 is accepted.

Table 9: Path coefficients, T-statistics, and P-values

Hypothesis	Path coeff., β	t-statistics	p-values	Remarks
H1: Store atmosphere \geq Impulse buying behaviour	0.253	5.18	0.00	Significant
H2: Store atmosphere \geq Situational factors	0.751	7.03	0.00	Significant
H3: Situational factors \geq Impulse buying behaviour	0.334	4.41	0.00	Significant

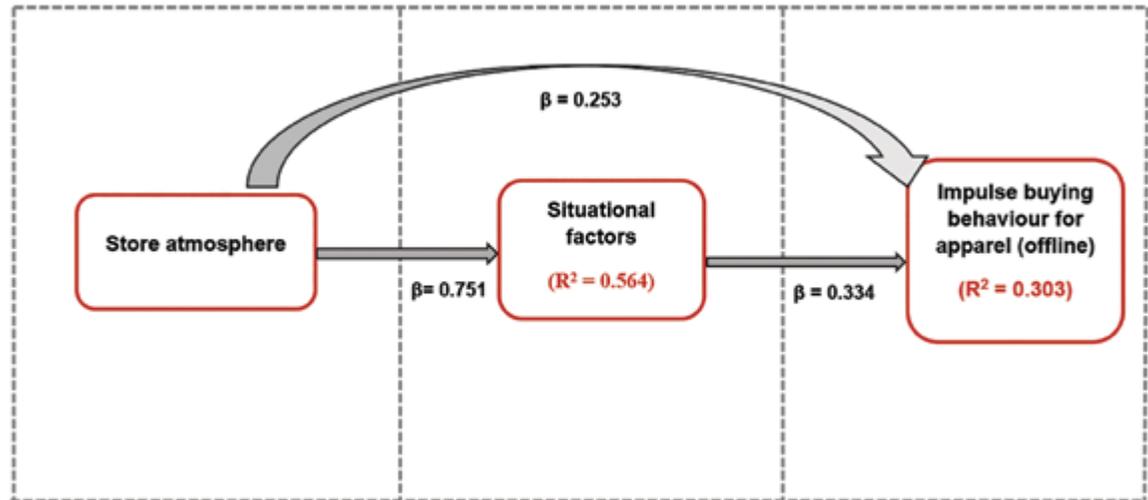


Figure 3: Final research framework of IMBB of apparel consumer

Similarly, store atmosphere contributes 75.1% to situational factors, while situational factors account for 33.4% of the direct influence on impulse buying behaviour (see Figure 3). With a t-statistic of 7.03 > 1.96 and a p-value of 0.00 < 0.05, store atmosphere positively and significantly impacts situational factors. Situational factors also significantly influence impulse buying, with a t-statistic of 4.41 > 1.96 and a p-value of 0.00 < 0.05. Thus, hypotheses H2 and H3 are accepted, confirming that both store atmosphere and situational factors positively affect impulse buying behaviour for apparel.

On the other hand, the results presented in Table 10 show an indirect effect relationship between the latent constructs. Thus, a partial mediation exists. The path analysis assessment (0.250) found a significant association between store atmosphere with impulse buying behaviour based on situational factors as mediators. In addition to the significant

indirect effect ($\beta = 0.250, p < 0.001$), the direct effect of store atmosphere on impulse buying behaviour remained significant after accounting for the mediator, although its strength was reduced, indicating partial mediation. To further establish the type of mediation, the direct effect of store atmosphere on impulse buying behaviour was examined both before and after the inclusion of situational factors as a mediator. Without considering the mediator, the direct path coefficient was $\beta = 0.430$ ($t = 7.860, p < 0.001$), indicating a strong and significant relationship. After including situational factors, the direct effect decreased to $\beta = 0.280$ ($t = 5.120, p < 0.001$), but remained statistically significant. This reduction in the direct effect, while maintaining significance, confirms the presence of partial mediation. The t-statistic is greater than 1.96, while the p-value is significant at a 5% level, less than 0.05. Hence, hypothesis H4 is accepted.

Table 10: Specific indirect effect of situational factors

Path analysis (Hypothesis 4)	Direct effect		Indirect effect	t-statistics	p-values	Remarks
	Before mediation	After mediation				
H4: Store atmosphere \geq Situational factors \geq Impulse buying behaviour	0.430	0.280	0.250	4.055	0.00	Significant

4 Conclusion

In conclusion, this study delved into the intricate interplay between store atmosphere, situational factors and impulse buying behaviour among apparel consumers. Through a comprehensive analysis of the impact of atmospheric cues, such as store ambience, design, social factors and clothing touch, as well as situational factors, such as promotional offers, time availability, money availability, customer mood and the presence of others, this research provides valuable insights into the drivers of impulsive purchasing decisions in the apparel retail environment. The findings of this study underscore the significant influence of store atmosphere and situational factors on consumers' impulse buying behaviour. A captivating store ambience, carefully crafted through visual, auditory and olfactory cues, can evoke positive emotions, enhance mood and stimulate impulsive purchases among apparel consumers [21]. Additionally, situational factors such as promotional offers and time constraints were identified as key determinants that shape impulse buying tendencies, with discounts and limited-time promotions creating a sense of urgency and scarcity, thereby driving impulsive purchases. Furthermore, this research highlights the interactive nature of store atmosphere and situational factors, emphasizing the need for retailers to consider both aspects in tandem to effectively stimulate IMBB for apparel consumers. By strategically designing store environments to evoke specific emotions, aligning promotional strategies with consumer preferences and needs, and creating a sense of excitement and urgency, retailers can optimize their efforts to drive impulse purchases among apparel consumers [49, 75].

4.1 Theoretical implications

This study contributes to theoretical implications by empirically testing developed relationships, thereby aiding theory verification. It addresses the growing interest in impulse purchases by developing a framework that includes factors of store atmosphere and situational factors affecting impulse buying behaviour in apparel. The study's findings can help researchers apply this conceptual framework to other areas of consumer purchasing behaviour [57, 58, 63, 64].

Second, this study shows that situational factors such as time availability, money, presence of others, promotional offers and mood mediate the relationship between store atmosphere and impulse buying in apparel consumers [61, 64]. This mediation effect, previously unexplored, suggests that individuals with more time and money are more responsive to atmospheric cues and more likely to make impulse purchases. Understanding these situational factors can help tailor marketing tactics to target consumers' financial situations. The study's findings enhance the understanding of how situational factors stimulate impulse buying behaviour in apparel consumers [56, 62].

This study advances consumer behaviour theory by providing new insights into how store atmosphere and situational factors interact to influence impulse buying behaviour. It refines existing theoretical frameworks such as S-O-R theory and decision-making models by considering how contextual influences shape consumer responses in complex retail environments.

4.2 Practical implications

The practical implications of these findings offer valuable insights for retailers. By understanding the

connection between store atmosphere, situational factors and impulse buying, retailers can optimize their marketing, merchandising and store layouts to encourage spontaneous purchases. Additionally, technology and data analytics can personalize the shopping experience with targeted promotions and recommendations [66, 87, 88].

Furthermore, the study's results can guide store managers in creating comfortable atmospheres that encourage impulse purchases. Managers should invest in improving store ambience, including enhancing salespeople's attitudes, creating appealing layouts and presenting products attractively. These strategies can boost impulse buying and help develop effective promotional programs targeting impulsive apparel buyers [48, 68, 69]. The findings also imply that managers should carefully design the atmosphere of apparel retail stores and websites for highly interested customers, as they are more likely to make impulse purchases [89, 90].

5 Limitation and future recommendation

This study's findings may lack generalizability beyond the specific context and sample used, as it focuses on a particular geographic region, type of retail environment or demographic group. Additionally, the study may not have accounted for all potential mediating and moderating variables that could influence the relationship between store atmosphere, situational factors and impulse buying behaviour.

Future research could explore other product categories such as FMCG, electronic items, beauty products and fashion accessories. It could also investigate how digital atmospherics (such as website design, visual aesthetics and online mood cues) influence consumer decision-making, emotional engagement and purchase intent. Research could also investigate the role of interactive design elements, such as virtual try-ons or augmented reality features,

in creating an immersive shopping environment that drives customer satisfaction and loyalty.

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Data availability statement: The dataset contains retailer and shopper information, including sensitive participant details that cannot be anonymized without compromising the integrity of the research. Therefore, the data cannot be publicly deposited. However, the dataset may be made available by the corresponding author upon justified request.

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Impact of Fashion Influencers on Generation Z and Millennials Purchasing Behaviour

Vpliv modnih vplivnežev na nakupne navade generacije Z in milenijcev

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Abstract

In the age of social media, influencers are an important marketing tool, especially when it comes to their influence on Generation Z and Millennials as they use influencer communication techniques. The article summarises the findings of various studies in which the authors study the influence of online influencers on purchasing behaviour when it comes to fashion products, emphasising the importance of authenticity, originality and transparency. The research also shows that an appropriate content strategy is important for the credibility of influencers, who, through thoughtful storytelling techniques, encourage favourable responses from followers and share content on social networks. In the study, we examined the influence of fashion influencers on the purchasing behaviour of Instagram users, especially when it comes to young people. Our objective was to analyse the impact of influencers, the power of their tools and how they are perceived by consumers. The aim of the research was to contribute to understanding the role of influencers in young people's fashion purchases. Our research shows that Instagram influencers play an important role in the purchasing decisions of respondents who actively follow fashion content. The research results show that official profiles and user reviews have a greater impact on purchasing decisions than sponsored posts by influencers. There is also moderate scepticism regarding the accessibility of fashion influencer profiles, which is reflected in the relatively low share of those who made purchases based solely on their recommendations. Nevertheless, respondents regularly buy textiles online, mainly for practical reasons, e.g. greater choice and easier shopping. Sustainability is also important in their purchasing decisions. The results can significantly contribute to effective marketing strategies when it comes to fashion purchases.

Keywords: digital marketing, influencer marketing, Instagram, fashion, Gen Z and Millennials



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Izvleček

V času družbenih omrežij so vplivneži z uporabo različnih komunikacijskih tehnik pomembno marketinško orodje, še posebno ko gre za njihov vpliv na generacijo Z in milenijce. V članku so povzete ugotovitve različnih raziskav, v katerih avtorji proučujejo vpliv spletnih vplivnežev na nakupno vedenje, ko gre za modne izdelke, kjer avtorji poudarjajo predvsem pomen avtentičnosti, originalnosti in transparentnosti. Raziskave tudi kažejo, da je ustrezna vsebinska strategija pomembna za verodostojnost vplivnežev, ki s premišljenimi tehnikami pri-povedovanja zgodb spodbujajo ugodne odzive sledilcev in delijo vsebine na družbenih omrežjih. Z raziskavo smo želeli proučiti vpliv modnih vplivnežev na nakupno vedenje uporabnikov Instagrama, še posebno ko gre za mlajšo populacijo. Naš cilj je bil analizirati vpliv vplivnežev, moč njihovih orodij in kako jih dojemajo kupci. Namen raziskave je bil prispevati k razumevanju vloge vplivnežev pri modnih nakupih mladih. Naša raziskava kaže, da imajo Instagram vplivneži pomembno vlogo pri nakupnih odločitvah anketirancev, ki aktivno spremljajo modne vsebine. Izsledki prav tako nakazujejo, da imajo uradni profili in ocene uporabnikov večji vpliv na odločitve o nakupu kot sponzorirane objave vplivnežev. Zmeren dvom se pojavi tudi glede dostopnosti profilov modnih vplivnežev, kar se odraža v relativno nizkem deležu tistih, ki so nakupe opravili zgolj na podlagi njihovih priporočil. Kljub temu anketiranci redno kupujejo tekstil preko spleta, predvsem iz praktičnih razlogov, kot sta večja izbira in lažji nakup. Trajnost je tudi pomembna pri njihovih odločitvah o nakupu. Izsledki raziskave lahko pomembno prispevajo k učinkovitim marketinškim strategijam, ko gre za nakupe modnih izdelkov. Ključne besede: digitalni marketing, vplivnostni marketing, Instagram, moda, generacija Z in milenijci

1 Introduction

In an era dominated by social media, online influencers have become an important marketing tool for brands seeking to connect with their target customers. In the time of daily connectivity, especially among Generation Z (Gen Z) on social media, influencers build their influence with brands by regularly posting texts, images and videos; this is especially evident among the younger generation.

1.1 The main area

Contemporary research on consumer behaviour increasingly highlights the influence of social media marketing, particularly through influencers, on younger demographics. A distinct group of micro-influencers has emerged, recognised for their perceived authenticity, personal engagement with followers and creative talent. Their success is largely driven by the followers who use them as models in shaping their brands [1].

The rise of virtual influencers further expands

this landscape. Their effectiveness seems closely tied to traits such as emotional warmth, relatability and credibility [2]. The broader context of digital transformation – including advancements in artificial intelligence and the growing role of social media – has considerably reshaped consumer decision-making processes [3]. Retail strategies are now influenced by a mix of channel characteristics and consumer expectations, leading to complex omnichannel marketing approaches [4]. In this dynamic, influencer marketing thrives especially when rooted in transparency and a sense of authenticity [5].

Influencers utilise their online presence to showcase curated lifestyles, perspectives and talents that resonate with specific brand values, forging mutually beneficial relationships. This alignment promotes both social influence and financial opportunities. Micro-influencers – typically with follower counts ranging from 1,000 to 100,000 – often concentrate on niche areas, enabling them to maintain a high

level of trust and perceived authenticity among their audience [6]. Their strategy involves fostering a sense of closeness and collaboration with their followers, blurring the line between the audience and influencer.

In a study involving more than 12,000 participants [1], micro-influencers were found to gain traction on social networks by capitalising on traits such as authenticity, openness and creative communication. Their ability to present themselves through music, art and social engagement significantly enhances their competitive edge. These influencers are most active in sectors such as fashion, beauty, tourism, food and beverages – product categories that are inherently expressive and sensitive to trends and pricing. The study also reveals generational differences; while older generations like Generation X and the so-called Silver Surfers often pursue financial rewards, younger audiences, especially Gen Z, are driven by a desire for recognition. Gender has a limited role; however, financial motives are more evident in entertainment-related sectors, whereas fame-driven individuals focus on interactive areas like music and social exchange. In fashion and tourism, micro-influencers exert especially strong influence and their self-branding revolves around establishing exclusivity while fostering a sense of belonging.

1.2 Aim

Further research focuses on the fashion industry and supports these insights. It confirms that micro-influencers are often more effective than their macro counterparts in driving purchase decisions due to the higher trust and authenticity they are perceived to embody [7]. Younger generations, particularly Gen Z and Millennials, are especially responsive to Instagram-based marketing strategies. Studies indicate that women are more susceptible to impulsive purchases triggered by emotionally charged content [8]. Successful Instagram strategies often include storytelling techniques that connect emotionally, highlighting the importance of credible and knowledgeable influencers who foster positive attitudes toward fashion trends [9].

The impact of influencers on Gen Z is especially pronounced. Their credibility directly shapes brand perception and purchase intention, with 85% of young consumers acknowledging that such influencers affect their buying choices [10, 11]. Instagram remains the leading platform where Gen Z prefers to engage with product-related content and lifestyle narratives. In the highly competitive online fashion sector, this level of influence translates into a significant advantage.

Effective influencer marketing also relies on well-crafted content strategies. High-quality storytelling – using methods like brand evaluations, emotional connections, and identity-building – has proven effective in generating favourable electronic word-of-mouth (eWOM) [12]. The creative use of elements such as captions, emojis and visually engaging posts further boosts user engagement, especially when used by influential personalities [13]. Studies measuring consumer response indicators such as purchase intent, brand perception and impulse buying demonstrate tangible economic impacts, including improved visibility and consumer interaction [14, 15].

Finally, consumer attitudes in regional markets such as Slovenia reveal a strong preference for sustainable and certified eco-friendly textile products. These items are perceived as more costly but also more responsible and aligned with sustainability values [16].

Successful influencer strategies consistently focus on producing content that is authentic, trustworthy and tailored to the target audience. These strategies often include storytelling and platform-specific adaptations. Influencers vary from celebrities to niche experts, yet the common goal remains, i.e. creating engaging, high-quality content that resonates with their community while enhancing brand visibility and driving consumer behaviour.

1.3 Research field

In the research, we focused on consumer purchasing behaviour, which is one of the most interesting

research areas in marketing, as it is influenced by a multitude of factors that, in various combinations, lead the consumer to make a purchase. Consumer purchasing behaviour is a complex process. Many sciences (sociology, psychology, anthropology, economics) are involved in studying consumer behaviour. We will focus on influencers who impact their followers with their behaviour.

Influencers are individuals who have a large reach and influence on social media and can guide the purchasing decisions and behaviour of their followers with their opinions, recommendations and content. They usually specialise in a specific field, e.g. fashion, technology, fitness or travel, and work with brands to promote products or services. Their influence is based on authenticity, follower engagement and the ability to create compelling content. Fashion influencers have a strong impact on young people (Gen Z and Millennials), as they shape fashion trends, encourage purchasing decisions and promote certain brands through social media. Their authenticity and accessibility create a sense of trust, which is why young people often imitate their style and follow their recommendations. In addition, influencers also affect values such as sustainable fashion, ethical production and individuality, which changes the way young people perceive and consume fashion.

2 Methods

In the research, we used a quantitative online survey method, as we wanted to shed light on various aspects that influence purchasing behaviour and provide insight into the power of influencers when it comes to fashion. Our objective was to analyse the impact of influencers, the power of their tools and how they are perceived by buyers, especially when it comes to young people. The aim of the research was to contribute to understanding the role of influencers when it comes to young people's fashion purchase decisions.

We wanted to analyse the data obtained using a survey questionnaire on the importance of individ-

ual factors with which influencers influence the purchase of fashion products by Gen Z and Millennials and above all, to interpret the obtained results and verify the hypotheses set. Moreover, based on the research conducted, we wanted to provide recommendations for further research and practice.

2.1 Research plan

The online questionnaire consisted exclusively of closed-ended questions. This method was chosen to efficiently gather responses from Instagram users about their behaviours and attitudes related to fashion influencers. A structured questionnaire was developed, consisting of exclusively closed-ended questions (multiple choice and Likert-type scales). The survey instrument was constructed based on the themes identified in the literature on influencer marketing and consumer behaviour. Questions consequently covered topics such as Instagram usage habits, engagement with fashion content, perceptions of influencer credibility and self-reported purchasing behaviour influenced by various sources (influencers, official brand content, peer reviews). Where possible, we drew on or adapted items from previous studies to ensure content validity, e.g. we included a question with a 5-point scale asking respondents how often Instagram advertising influences their attitude toward fashion products (from "Never" to "Almost always"), similar to the measures used in prior social media impact studies. Some questions were tailored to our context (e.g. naming Instagram specifically, or local examples), and the overall questionnaire was reviewed by two marketing faculty members for clarity and relevance.

Before full deployment, the survey underwent a brief pre-test with a small group of five individuals from the target population (university students and young professionals) to ensure that questions were clear and interpreted as intended. This feedback led to minor wording adjustments. No formal pilot study or scale validation (e.g. factor analysis) was conducted due to time constraints and the primarily exploratory nature of some questions – this

is acknowledged as a limitation. However, many questions were straightforward factual or preference items (e.g. “Do you follow fashion content on Instagram? Yes/No,” or selecting which content type influences you most), which mitigated the need for extensive psychometric validation of scales.

The survey was conducted via the website Ika.si. Respondents accessed the online survey via a web link. Our sample consisted of everyone who uses Instagram. It comprised several sections, namely Demographics (age, gender, education), Instagram usage (frequency of use, following of fashion content), Content Influence – which types of Instagram content (sponsored influencer posts, friends’ posts, official brand profiles, user reviews etc.) are most persuasive, Behaviour and Attitudes – including whether the respondent follows fashion influencers and whether they have ever purchased clothing based solely on an influencer’s recommendation, and perceptions regarding the fashion industry and sustainability. The survey was anonymous and took approximately 5–7 minutes to complete.

The sample was a non-probability sampling, i.e. a convenience sampling. We accessed the sample by sharing the link to the survey on the social networks Facebook and Instagram, through the online classrooms of marketing and informatics students at the Ljubljana School of Business, and friends/family. We also asked social network users to forward the survey to their friends and acquaintances. The online survey was available for 14 days. We expected approximately 100 appropriate responses for analysis; however, in the end, we received 185 completed questionnaires, 183 of which were completed correctly and met all the conditions.

The obtained data was then analysed with SPSS and MS Excel, using various statistical methods. We first performed descriptive statistics to summarise the data (frequencies, percentages, means, standard deviations) for all survey questions. This provided an overview of sample characteristics and general trends (e.g. proportion of respondents following fashion content, or average self-reported influence

of Instagram advertising). These descriptive results are presented in a series of tables for clarity.

To test our hypotheses, we employed inferential statistical tests. In particular, we used the chi-square test of independence for hypotheses that involved categorical comparisons (e.g. comparing groups of respondents on whether they have made a purchase based on an influencer’s recommendation). The chi-square test is appropriate for identifying whether differences in proportions between groups are statistically significant. For each relevant hypothesis, contingency tables were constructed (cross-tabulating, e.g. age group by following fashion content, or following influencers by purchase behaviour), and the chi-square statistic (χ^2) and p-value were calculated. A significance level of $\alpha = 0.05$ was used to determine statistical significance. We reported the p-values and established whether the hypotheses were supported or not.

2.2 Hypotheses

Drawing on the literature review and research objectives, we formulated the following hypotheses:

Hypothesis 1 (H1): Generation Z and Millennials follow fashion content on Instagram more than older generations.

This hypothesis posits a generational difference in engagement with fashion-related content on Instagram. Younger users, being digital natives, are expected to have higher involvement in following fashion influencers or brands on social media¹. We anticipate that respondents in Gen Z/Millennial age ranges will report a higher rate of following fashion content compared to older respondents (e.g. those above Millennial age).

Hypothesis 2 (H2): Instagram sponsored posts by influencers are the most likely to persuade respondents to buy fashion products.

¹ <https://www.surveymonkey.com/curiosity/gen-z-social-media-and-shopping-habits/>

This hypothesis reflects the assumption that influencer advertisements (sponsored posts) have a particularly strong influence on consumer buying decisions, perhaps more so than other content on Instagram (such as brand's own posts or peer content). The rationale comes from studies indicating that sponsored influencer content can be highly effective, e.g. one Gen Z study found that 80% of participants responded very favourably to sponsored influencer material². We therefore expect sponsored posts to be ranked by respondents as the content type most likely to convince them to buy fashion items.

Hypothesis 3 (H3): The respondents who follow fashion influencers are more inclined to buy clothes based solely on their recommendations.

Theoretical justification for this hypothesis lies in the social influence and parasocial relationship theory: individuals who choose to follow fashion influencers likely trust them or find their content appealing, which should translate into a higher propensity to act on their recommendations³. Prior research shows a strong correlation between following influencers and being influenced by them in purchasing contexts⁴. We expect to find that the respondents in our sample who follow fashion influencers have a significantly higher rate of having made a purchase due to an influencer's recommendation, compared to those who do not follow influencers.

Hypothesis 4: The respondents who follow fashion content are more often willing to buy clothes simply because of influencer recommendations.

This hypothesis is related to H3; however, it extends the concept to anyone engaging with fashion

content (not only specific influencer accounts). The idea is that if a person is interested in fashion content on Instagram – whether through influencers, brand pages, or hashtags – they are immersed in the social media fashion culture and thus more open to influence from any fashion-related source. Essentially, being a follower of fashion content creates a receptive mindset towards influencer suggestions. Industry surveys support this notion: users who follow brands or fashion pages on social media are much more likely to purchase products promoted on these platforms⁵. We hypothesise that the respondents who indicate they follow fashion content on Instagram will show a greater willingness (and actual behaviour) to buy items purely due to influencer endorsements, compared to those who do not follow fashion content.

3 Results and discussion

A total of 183 respondents participated in the survey. The key demographic characteristics are summarised in Table 1. The majority of respondents were female (approximately 78%), reflecting a gender imbalance in our sample. In terms of age, our sample skewed slightly older than the primary target of Gen Z: more than half of respondents (56%) were over 36 years old, while about one-third (31%) were between 19 and 25 years old; the remainder fell between 26 and 35. This indicates that a significant portion of participants were older Millennials or even Gen X, which is noteworthy for interpreting the results of H1 (since we have a substantial comparison group of older vs. younger). Regarding education level, 75% of respondents reported having higher or university-level education, and only 5% had a vocational (secondary) education, meaning the sample was relatively well-educated.

These demographics highlight a limitation, the sample is namely not representative of the general

2 <https://wsj.westsciences.com/index.php/wsis/article/view/317#:~:text=authenticity%20Transparency%20%2872.5,of%20Generation%20Z%20in%20Indonesia>
3 <https://www.nature.com/articles/s41599-023-02512-1#:~:text=credibility%20and%20purchase%20intention%20by,moderating%20effect%20on%20the%20relationship>
4 <https://wsj.westsciences.com/index.php/wsis/article/view/317#:~:text=locations,percent%20of%20users%20preferred%20partnerships>

5 <https://www.surveymonkey.com/curiosity/gen-z-social-media-and-shopping-habits/>

population of Instagram users in terms of gender and age distribution. Instead, it over-represents women and includes a large fraction of older individuals. This bias will be considered when discussing the generalisability of findings. Nevertheless, it also

provides an interesting internal comparison – since we do have respondents across different age groups, we can observe generational differences within our data, albeit within a convenience sample.

Table 1: Demographic data

Demographic data	Answers	Frequency	Percentage (%)	Cumulative (%)
Gender	Female	142	78%	78
	Men	41	22%	100
Age	0–18 years	0	0%	0
	19–25 years	31	17%	17
	26–35 years	45	25%	42
	36–45 years	60	33	74
	46 years and older	47	26	100
Education	Primary school	0	0	0
	Secondary school	10	5	5
	High education	35	19	25
	Higher education	68	37	62
	University education	70	38	100
	Total	183	100	

Nearly all respondents were active Instagram users, as expected by our inclusion criteria. Table 2 shows that the vast majority of the respondents (76%) use Instagram, and the majority of Instagram users (91%) spend up to two hours per day on the platform. 62% of the respondents follow fashion content on Instagram. About half of the respondents (49%) believe that Instagram advertising rarely influences their attitude towards fashion products. The mean of the responses for the impact of Instagram advertising ($AM = 2.6$, $SD = 0.9$) shows that the majority of the respondents tend to be moderately influenced by Instagram advertising.

We specifically explored which types of Instagram content respondents find most convincing when it comes to making purchasing decisions for fashion products. This addresses H2. We provided multiple options and allowed respondents to select all that apply. The content types included: sponsored influencer posts, posts by friends/acquaintances, official brand profiles/posts, user reviews or opin-

ions (e.g. in comments or Q&A stories), and video tutorials or product demonstration posts. Table 3 summarises the results of this question.

Table 3 shows the responses when the respondents were asked which types of content on Instagram most persuade them to buy. Official brand profiles convince the most respondents (59%). Ratings and opinions of users (48%) also have a significant impact on the purchase, as users often trust the experiences and reviews of other consumers. Sponsored posts by influencers (15%) proved to be the least convincing in this survey.

The results from Table 3 are somewhat striking: official brand profiles outranked influencer posts by a large margin in terms of perceived influence on purchasing. This finding runs counter to the assumption in H2 that influencer-sponsored posts would dominate. Instead, it appears that respondents rely more on direct brand communications and peer feedback. This could reflect a scepticism towards influencer promotions – possibly viewing them as ads – or simply that

Table 2: Using Instagram and following fashion content on Instagram

Questions	Answers	Frequency	Percentage (%)	Cumulative (%)
Do you use the social network Instagram?	Yes	136	76	76
	No	42	24	100
	Total respondents	178	100	
How much time do you spend on Instagram per day?	Less than 1 hour per day	63	46	46
	1–2 hours per day	61	45	91
	3–4 hours per day	12	9	100
	More than 5 hours per day	0	0	100
	Total respondents	136	100	
Do you follow fashion content on this platform?	Yes	84	62	62
	No	52	38	100
	Total respondents	136	100	
Do you think Instagram advertising influences your attitude towards fashion products?	1 – Never	14	10	10
	2 – Rarely	52	39	49
	3 – Sometimes	48	36	85
	4 – Often	16	12	97
	5 – Almost always	4	3	100
	Total respondents	134	100	
Mean of the responses		2.6	Std. deviation	0.9

official brand pages often provide reliable information (e.g. product details, new arrivals) that directly facilitates purchase decisions. The relatively high trust in user reviews (48%) aligns with global trends where consumers trust peer experiences and reviews as much as or even more than traditional advertising.

Our survey included questions to gauge how

many respondents actively follow fashion influencers on Instagram and whether they imitate or take inspiration from these influencers, as well as if they have ever made a purchase based solely on an influencer's recommendation. These questions help address H3 and H4 by segmenting the sample according to their engagement level.

Table 3: What types of content on Instagram convince you the most to buy?

What types of content on Instagram convince you the most to buy? – more possible answers	Frequency	Valid	Percentage (%)
Sponsored influencer posts	20	130	15
Posts by friends and acquaintances	51	130	39
Official brand profiles	77	130	59
User reviews and opinions (comments, Q&A story)	62	130	48
Video tutorials and product demonstrations	39	130	30
Total respondents		130	

Table 4 shows that 46% of the respondents regularly follow fashion influencers, 16% only sometimes, while 38% do not follow fashion influencers. The largest share of the respondents (42%) rarely follow

ideas and styles recommended by influencers and 25% of the respondents do not imitate them at all. The mean of the responses for the variable following fashion influencers (AS = 2.2, SD = 0.9) shows that

while most respondents follow influencers, they only occasionally or rarely imitate them in fashion trends. Only 30% of the respondents have purchased clothing solely on the recommendation of an online influencer.

Table 4: Impact of content and influencers

Questions	Answers	Frequency	Percentage (%)	Cumulative (%)
Do you follow any fashion influencers?	Yes	61	46	46
	No	51	38	84
	Sometimes	22	16	100
	Total respondents	134	100	
Do you want to imitate their ideas, styles, recommendations on fashion trends?	1 - Never	34	25	25
	2 - Rarely	56	42	67
	3 - Sometimes	33	25	92
	4 - Often	11	8	100
	5 - Almost always	0	0	100
	Total respondents	134	100	
	Mean of the responses	2.2	Std. deviation	0.9
Have you ever purchased clothes based exclusively on the recommendation of an online influencer?	Yes	40	30	30
	No	94	70	100
	Total respondents	134	100	

Table 5: The respondents' opinions on actual image of fashion industry

Questions	Answers	Frequency	Percentage (%)	Cumulative (%)
Do you think that the fashion trends predicted by online influencers are important to you and affect your purchasing behavior?	1 - I don't know	3	2	2
	2 - Never	43	33	35
	3 - Rarely	46	35	70
	4 - Sometimes	35	27	97
	5 - Often	4	3	100
	6 - Almost always	0	0	100
	Total respondents	131	100	
	Mean of the responses	3.0	Std. deviation	0.9
Do you think fashion influencers portray a realistic image of the fashion industry?	1 - Yes	5	4	4
	2 - Partially	75	57	61
	3 - No	51	39	100
	Total	131	100	
	Mean of the responses	2.4	Std. deviation	0.6
Do you think fashion influencers portray a realistic lifestyle?	1 - Yes	1	1	1
	2 - Partially	39	30	31
	3 - No	91	69	100
	Total respondents	131	100	
	Mean of the responses	2.7	Std. deviation	0.5

Table 5 shows that 68% of the respondents on their Instagram profiles are not relevant to their shopping process. Only 4% of respondents believe believe that fashion trends posted by influencers

that influencers represent the real fashion industry. Most respondents (57%) estimate that the portrayal of the fashion industry is only partly realistic. The average agreement (AS = 2.4, SD = 0.6) is closer to the “Partially” answer, confirming that the general opinion in the sample is reserved: most do not believe that influencers fully capture reality, but are aware that some aspects of fashion are still reflected. As many as 69% of the respondents believe that fashion influencers do not portray a realistic lifestyle

and additional 30% estimate that this portrayal is only partially realistic.

Table 6, which shows how respondents assess their attitude towards fashion, shows that 39% of the respondents follow fashion, but do not necessarily dress according to trends, 31% follow fashion only occasionally, and 18% of respondents regularly follow fashion and trends. The mean (AS = 2.7, SD = 1.0) shows that most respondents tend to follow fashion moderately.

Table 6: Attitude towards fashion

Question	Answers	Frequency	Percentage (%)	Cumulative (%)
How would you rate your attitude towards fashion?	1 -Not interested	18	10	10
	2 - I only occasionally follow fashion trends	53	31	41
	3 - I follow fashion, but I don't dress according to trends	67	39	80
	4 - I regularly follow fashion and trends	31	18	98
	5 - I am very involved in the fashion industry (e.g., blogger, stylist, influencer, fashion designer)	4	2	100
	Total respondents	173	100	
	Mean of the responses	2.7	Std. deviation	1.0

Table 7 shows how often the respondents buy fashion products (textiles) online, showing that as many as 34% of the respondents buy textiles online frequently, 27% of them sometimes and 22% rarely shop online. The mean of the responses (AS = 3.0,

SD = 1.1) indicates that the overall level of online shopping is moderate, with a standard deviation of 1.1 indicating that the habits of the respondents are relatively diverse.

Table 7: Online purchasing

Question	Answers	Frequency	Percentage (%)	Cumulative (%)
Do you buy fashion products (textiles) online?	1 - Never	16	9	9
	2 - Rarely	40	23	33
	3 - Sometimes	47	27	60
	4 - Often	59	34	94
	5 - Almost always	10	6	100
	Total respondents	172	100	
	Mean of the responses	3.0	Std. deviation	1.1

Table 8 displays what most attracts the respondents to buying clothes online and shows that the largest proportion (60%) are most attracted by the greater choice of products, with 57% also pointing out the ease of delivery and returns. Furthermore,

lower prices (43%) and other benefits (discounts, promotions, loyalty programmes) (46%) influence the decision. Influencer recommendations (5%) are by far the least common reason to buy online.

Table 8: What attracts you most to online clothing shopping?

What attracts you most to online clothing shopping?	Frequency	Valid	Valid (%)
Lower prices than in stores	71	167	43
Greater choice of products	100	167	60
Influencer recommendations	8	167	5
Easy delivery and returns	95	167	57
Other benefits (discounts, promotions, loyalty programs)	76	167	46
Total respondents		167	

In Table 9, which shows whether the respondents are interested in the sustainability aspect (eco materials, ethical production), we can see that the majority of the respondents (68%) occasionally take

sustainability aspects into account when buying clothing. Only 6% always buy sustainable products, while 26% do not pay attention to this aspect.

Table 9: Sustainability

Question	Answers	Frequency	Percentage (%)	Cumulative (%)
Are you interested in the sustainable aspect (eco materials, ethical production) when buying clothes?	1 - Yes, I always buy sustainable products	11	6	6
	2 - Yes, I occasionally take this aspect into account	117	68	74
	3 - No, it doesn't matter to me when shopping	44	26	100
	Total respondents	172	100	
	Mean of the responses	2.2	Std. deviation	0.5

Table 10, which presents how much the respondents spend on online clothing purchases per month, shows that the vast majority of the respondents (75%) spend up to 100 euros per month on online clothing purchases, 20% spend up to 100 to 200 euros, only 5% of the respondents spend from

200 to 400 euros, and no one exceeds spending more than 400 euros.

With the descriptive results covered, we now proceed to hypothesis testing, where we tie these findings back to H1–H4, providing statistical evidence for confirmation or rejection.

Table 10: Monthly spending on online clothing purchases

Question	Answers	Frequency	Percentage (%)	Cumulative (%)
How much do you spend per month buying clothes online?	< 100 euros	124	75	75
	100–200 euros	33	20	95
	200–400 euros	9	5	100
	> 400 euros	0	0	100
	Total respondents	166	100	

Hypothesis 1. Generation Z and Millennials follow fashion content more on Instagram than older generations. NOT CONFIRMED

To test H1, we split respondents into two age groups: “younger” (Gen Z & Millennials, roughly ages 15–35) and “older” (above 35, which in our

sample primarily corresponds to Gen X). We then compared the proportions of each group that reported following fashion content on Instagram. However, since our sample had a skew (with 56% over age 36), we conducted a chi-square test to see if

the difference was statistically significant.

The Table 11 shows that out of 173 respondents, 130 (75.1%) provided valid answers and 43 (24.9%) did not, regarding whether people younger or older than 46 follow fashion content on the platform.

Table 11: Summary of statistical analysis characteristics

Case processing summary	Cases					
	Valid		Missing		Total	
	Number	Percentage (%)	Number	Percentage (%)	Number	Percentage (%)
Age younger older 46 Do you follow fashion content on this platform?	130	75.1	43	24.9	173	100.0

Based on the analysis of the results (Table 12), we can see that Gen Z and Millennials (aged 19 to 45) are slightly more likely to follow fashion content on Instagram compared to older generations (46 years and older). However, the chi-square test (Table 13) $p = 0.269$ ($p > 0.05$) shows that the difference is not statistically significant. Therefore, H1 cannot be confirmed.

Table 13: Chi-square test for age association and monitoring of fashion content

Chi-Square statistics	Value	df	Asymptotic significance (2-sided)	Exact sig. 2-sided)	Exact sig. (1-sided)
Pearson chi-square	1,222 ^{a)}	1	.269		
Number of valid cases	130				

Table 12: Age contingency table according to fashion content monitoring

Age younger older 46		Do you follow fashion content on this platform?	
		Yes	No
19–45 years	Count	69	38
	Percentage	64.5%	35.5%
46 years and older	Count	12	11
	Percentage	52.2%	47.8%
Total respondents	Count	81	49
	Percentage	62.3%	37.7%

^{a)} 0 cells (0.0%) have expected count less than 5. The minimum expected count is 8.67.

In other words, H1 was not confirmed by our data. The difference in following fashion content between younger and older respondents, while present in raw percentages, was not statistically reliable given our sample size and distribution. One likely reason is the composition of our “older” group: many older respondents in our sample might still be

relatively tech-savvy (since they came through social media channels), and a fair number of them do follow fashion content, making the gap smaller than hypothesised. In our data, 63% of the respondents under 36 followed fashion content, compared to about 55% of those aged 36 and above – a difference, but not a dramatic one. Therefore, H1 cannot be confirmed with statistical confidence, suggesting that in our sample, Gen Z/Millennial users were not significantly more likely to follow fashion content on Instagram than the older (Gen X) users.

Here’s a bar chart visualising the percentage of people in each age group who follow fashion content on the platform (Figure 1). People aged 19–45 are more likely to follow fashion content (64.5%)

compared to those 46 and older (52.2%). Conversely, a higher percentage of older users (47.8%) do not follow fashion content compared to younger users (35.5%).

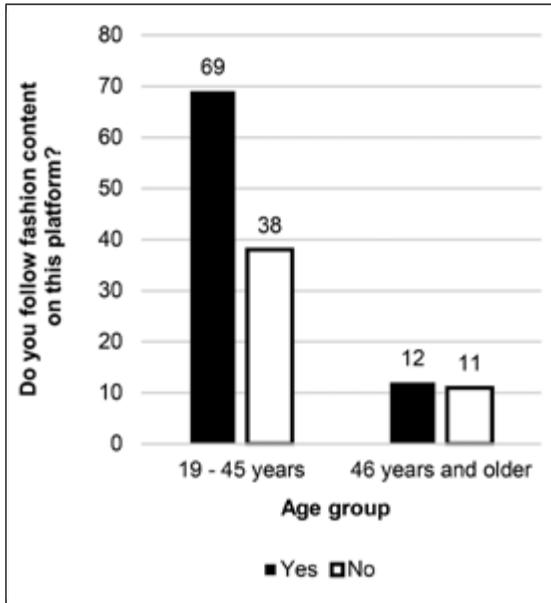


Figure 1: Fashion content following by age group

Hypothesis 2. Instagram sponsored posts by influencers are the most likely to persuade respondents to buy fashion products. NOT CONFIRMED

This hypothesis can be evaluated by looking at the results we described in Table 3 (content types that persuade purchases). The expectation was that sponsored influencer posts would rank highest.

Table 14 shows which types of content on Instagram most persuade the respondents to buy. Sponsored posts by influencers (15%) proved to be the least convincing in this survey. Official brand profiles (59%) have the most significant impact, indicating a high level of trust in direct, official information. Therefore, H2 cannot be confirmed.

Table 14 and Figure 2 illustrate how often different types of Instagram content convince users to make a purchase. The content types are ranked by their influence (frequency of selection) among the respondents. Official brand profiles are the most convincing, with the highest frequency (close to 80).

Table 14: What types of content on Instagram convince you the most to buy?

What types of content on Instagram convince you the most to buy?	Frequency	Valid	Percentage (%)
Sponsored influencer posts	20	130	15
Posts by friends and acquaintances	51	130	39
Official brand profiles	77	130	59
User reviews and opinions (comments, Q&A story)	62	130	48
Video tutorials and product demonstrations	39	130	30
Total respondents	-	130	

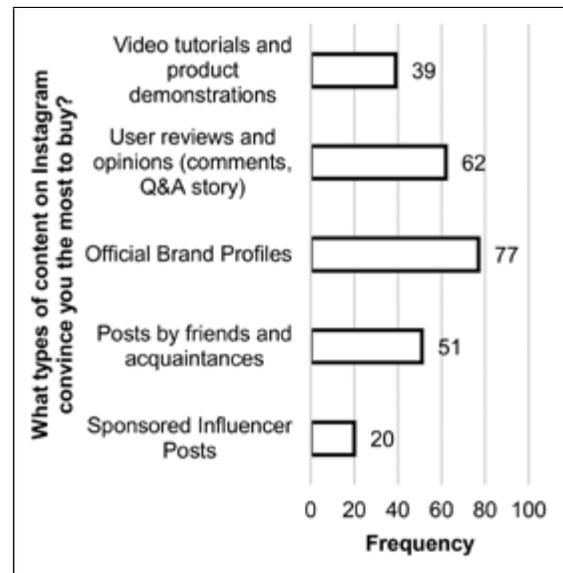


Figure 2: Instagram content types that influence purchasing decisions

This suggests that users trust and are most influenced by direct content from brands. User reviews and opinions (comments, Q&A story) come second (around 62), highlighting the importance of peer feedback and social proof in purchasing decisions. Posts by friends and acquaintances also have a significant impact (around 52), showing that personal connections can influence consumer behaviour. Video tutorials and product demonstrations (around 39) are moderately

persuasive, indicating that informative content helps in decision-making. Sponsored influencer posts have the least influence (about 20), suggesting a possible scepticism or lower trust in paid promotions compared to other content types.

Hypothesis 3: The respondents who follow fashion influencers are more inclined to buy clothes based solely on their recommendations. CONFIRMED

Hypothesis 3 deals with the relationship between following influencers and purchase behaviour. We

tested H3 by cross-tabulating “Do you follow any fashion influencers?” (Yes/No) with “Have you ever purchased clothing based exclusively on an influencer’s recommendation?” (Yes/No). A chi-square test was conducted to statistically verify this association.

The Table 15 indicates that out of 173 respondents, 130 (75.1%) provided valid answers and 43 (24.9%) did not regarding whether they follow any fashion influencers.

Table 15: Summary of statistical analysis characteristics

Case processing summary	Cases					
	Valid		Missing		Total	
	Number	Percentage (%)	Number	Percentage (%)	Number	Percentage (%)
Do you follow any fashion influencers? Have you ever purchased clothes based exclusively on the recommendation of an online influencer?	130	75.1	43	24.9	173	100.0

Based on the analysis of the results (Table 16), we can see that among those who regularly follow fashion influencers, as many as half (51.7%) have already made a purchase based solely on their recommendation. Among those who do not follow influencers, such purchases are extremely rare (only

6.1%). Based on the result of the chi-square test (Table 17), $p = 0.001$ ($p > 0.05$), H3 is confirmed, as there are statistically significant differences in purchasing behaviour between different groups of respondents. Those who follow influencers make such purchases more often; hence, we confirm H3.

Table 16: Contingency table to check H3

Cross-tabulation of responses			Have you ever purchased clothes based exclusively on the recommendation of an online influencer?	
			Yes	No
Do you follow any fashion influencers?	Yes	Count	31	29
		Percentage	51.7%	48.3%
	No	Count	3	46
		Percentage	6.1%	93.9%
	Sometimes	Count	5	16
		Percentage	23.8%	76.2%
Total respondents		Count	39	91
Percentage		30.0%	70.0%	

Those who follow fashion influencers indeed are far more likely to have been influenced to purchase fashion items solely on the basis of influencer

recommendations, compared to those who do not follow influencers. This finding makes intuitive sense and aligns with theoretical expectations: if

Table 17: Chi-square test results to check H3

Chi-square statistics	Value	df	Asymptotic Significance (2-sided)
Pearson chi-square	27.099 ^{a)}	2	< .001
Number of valid cases	130		

^{a)} 0 cells (0.0%) have expected count less than 5. The minimum expected count is 6.30.

Table 18: Summary of statistical analysis characteristics

Case processing summary	Cases					
	Valid		Missing		Total	
	Number	Percentage (%)	Number	Percentage (%)	Number	Percentage (%)
Do you follow fashion content on this platform? Have you ever purchased clothes based exclusively on the recommendation of an online influencer?	130	75.1	43	24.9	173	100.0

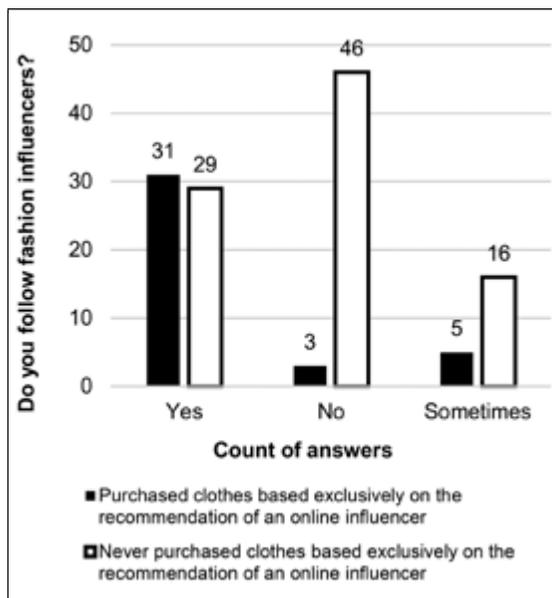


Figure 3: Purchases based on influencer recommendations vs. following fashion influencers

someone chooses to follow influencers, they are exposing themselves to persuasive content and likely have some level of trust or admiration for the influencer, which in many cases translates into trying out products the influencers recommend. Our result resonates with broader research that has found strong positive correlations between consumers'

engagement with influencers and their subsequent buying behaviour⁶.

The bar chart in Figure 3 visualises the relationship between following fashion influencers and purchasing clothes based on their recommendations. Among those who do follow influencers, more than a half (31 out of 60) have made a purchase based on their recommendation. The majority of those who do not follow influencers have not made such purchases (46 out of 49). Those who sometimes follow influencers are more likely not to purchase based on recommendations (16 vs. 5).

Hypothesis 4: The respondents who follow fashion content are more often willing to buy clothes simply because of influencer recommendations. CONFIRMED

Hypothesis 4 is closely related to H3; however, it broadens the scope to anyone following fashion-related content (not just influencers). In practice, to test H4 we looked at respondents who answered "Yes" to following fashion content on Instagram (which could include following brand pages, hashtags etc.),

⁶ <https://wsj.westsciences.com/index.php/wsis/article/view/317#:~:text=locations.percent%20of%20users%20preferred%20partnerships>

and compared their rate of purchasing based on influencer recommendations to those who answered “No” (do not follow any fashion content). Essentially, this is another 2 × 2 comparison: follow fashion content (Yes/No) vs. ever purchased due to influencer (Yes/No).

The Table 18 shows that out of 173 respondents, 130 (75.1%) provided valid answers and 43 (24.9%) did not regarding following fashion content on the platform and purchasing clothes based on an online influencer’s recommendation.

Based on the analysis of the results (Table 19), we can see that those who have already made a pur-

chase of clothing on the basis of a recommendation are higher in the group that follows fashion content (42%) than in those that do not follow it (10.2%). This means that following fashion content on Instagram increases the likelihood that respondents will decide to purchase clothing solely on the recommendation of an influencer. Based on the result of the chi-square test (Table 20) $p = 0.001$ ($p > 0.05$), H4 is confirmed, as there are statistically significant differences. Those who follow fashion content significantly more often make purchases of clothing based solely on recommendations. H4 is confirmed.

Table 19: Contingency table for checking H4

Cross-tabulation of responses			Have you ever purchased clothes based exclusively on the recommendation of an online influencer?	
			Yes	No
Do you follow fashion content on this platform?	Yes	Count	34	47
		Percentage	42.0%	58.0%
	No	Count	5	44
		Percentage	10.2%	89.8%
Total respondents		Count	39	91
Percentage		30.0%	70.0%	

Table 20: Chi-square test results to check H4

Chi-square statistics	Value	df	Asymptotic significance (2-sided)	Exact sig. (2-sided)	Exact sig. (1-sided)
Pearson chi-square	14.675 ^{a)}	1	< .001		
Number of valid cases	130				

^{a)} 0 cells (0.0%) have expected count less than 5. The minimum expected count is 14.70.

It is worth clarifying the conceptual distinction between H3 and H4 in light of these results. H3 isolated the effect of explicitly following influencer accounts, whereas H4 suggests that even following fashion broadly (which could mean one follows brand accounts or fashion news but not necessarily influencers) is associated with being influenced by influencers. The confirmation of H4 implies that an interest in fashion content in general predisposes consumers to be receptive to influencer suggestions. Possibly, those

who follow fashion content encounter influencers indirectly (e.g. via brand reposts or hashtags) and still absorb their recommendations. Alternatively, it might indicate that people passionate about fashion (as evidenced by following fashion content) are simply more open to trying new things, including those touted by influencers. Either way, H4 underscores a broader point: engagement with the fashion domain on Instagram, in any form, correlates with higher likelihood of influencer-driven purchasing.

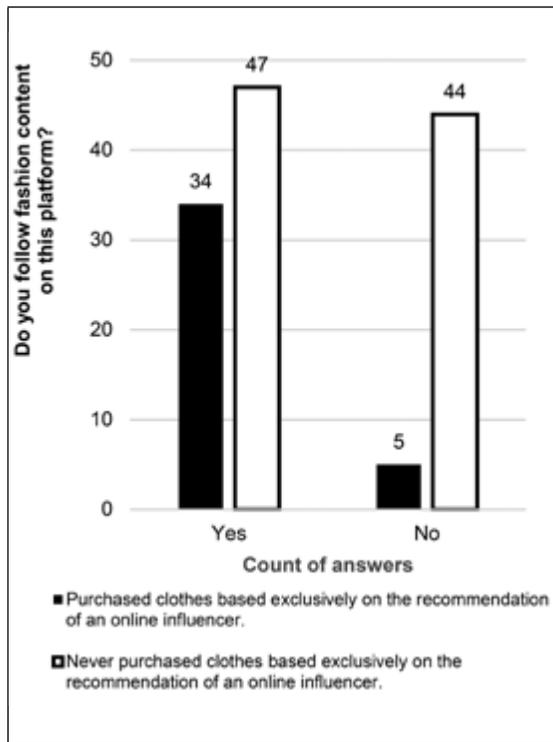


Figure 4: Purchases based on influencer recommendations vs. following fashion content

The bar chart in Figure 4 shows the relationship between following fashion content on the platform and purchasing clothes based on an influencer's recommendation. Among those who follow fashion content, 42% have purchased based on an influencer's recommendation (34 out of 81). Among those who do not follow, only 10.2% have done so (5 out of 49), with a strong majority not influenced.

This research makes several theoretical contributions to the study of influencer marketing and consumer behaviour. First, our results reinforce the idea that social media influencers can indeed alter consumer purchase behaviour; however, they add nuance to the understanding of how and when this influence occurs. The confirmation of H3 and H4 aligns with the social influence theory and the concept of parasocial relationships, i.e. consumers who engage with influencers or fashion content are more susceptible to being influenced in their purchasing decisions. This supports models that link influencer engagement to purchase intention via trust and

relationship-building⁷. Our findings provide empirical evidence of this link in a survey setting and in a new regional context (Slovenia), thus broadening the generalisability of existing theories beyond the commonly studied markets.

Secondly, our study contributes to the literature by comparing the persuasive power of different content sources on social media. The finding that official brand profiles and peer reviews were more influential than influencer posts (H2 not supported) challenges some assumptions in influencer marketing discourse. It suggests that, at least for the surveyed population, the credibility of information might outweigh the charisma of influencers. This insight contributes to theory by emphasising the role of content type and source credibility: it is not just who delivers a message (influencer vs. brand vs. peer) but the perceived trustworthiness of that source that affects consumer response. It echoes the Elaboration Likelihood Model (ELM) in that consumers might be processing influencer promotions more peripherally (and perhaps sceptically), whereas brand information and peer opinions could be seen as more central cues for decision-making⁸. Our results invite a theoretical reconsideration of when influencer content crosses the line to be seen as "advertising" by consumers, potentially triggering persuasion knowledge and scepticism (as evidenced by moderate trust and low direct conversion rates).

Additionally, our research offers a regional contribution by being, to our knowledge, one of the first studies focusing on influencer impact on fashion purchasing in Slovenia. It provides a point of comparison with studies from other countries. For example, Erwin et al. (2023) in Indonesia found

7 https://www.nature.com/articles/s41599-023-02512-1?error=cookies_not_supported&code=a773f28f-41f0-4ff9-bca8-6b05b52bc827#:~:text=The%20use%20of%20social%20media,moderating%20effect%20on%20the%20relationship

8 https://www.nature.com/articles/s41599-023-02512-1?error=cookies_not_supported&code=a773f28f-41f0-4ff9-bca8-6b05b52bc827#:~:text=The%20use%20of%20social%20media,moderating%20effect%20on%20the%20relationship

an extremely high rate (85%) of Gen Z consumers acknowledging influencer impact on purchases⁹, whereas our Slovenian sample shows a lower rate (30% have purchased based on influencer recommendation). This discrepancy might hint at cultural or market differences – perhaps Slovenian consumers are more sceptical or have different media consumption patterns. By documenting this difference, our study contributes to the theoretical conversation on how cultural context and market maturity influence the effectiveness of influencer marketing. It underscores that influencer marketing theories and models (mostly developed in large markets) should be tested in varying contexts; what holds in one culture may not exactly replicate in another. Our findings thus encourage an expansion of theory to incorporate context-dependent factors such as consumer scepticism, market size and prevalence of alternative information channels.

Finally, our inclusion of sustainability considerations ties our work into the theoretical discourse on ethical consumerism in the digital age. We observed that sustainability is important to our respondents, consistent with prior research in Slovenia and global Gen Z trends¹⁰. While we did not hypothesise directly about sustainability, the prominence of this theme in both our qualitative observations and respondents' attitudes suggests theoretical integration: influencer marketing's impact might increasingly depend on alignment with consumer values like sustainability. This contributes to emerging theories on the intersection of influencer marketing and brand activism/values-driven marketing.

4 Conclusion

Our research shows that Instagram influencers play an important role in the purchasing decisions of respondents who actively follow fashion content. Most respondents regularly buy textiles online, confirming the importance of the online environment for fashion shopping. The influence of Instagram content and influencers is significant, and purchasing behaviour also depends on other factors, e.g. personal interests, perceptions of influencers' authenticity and brand marketing strategies. The research results show that official profiles and user ratings have a greater influence on purchasing decisions than sponsored posts by influencers. There is also a moderate scepticism regarding the availability of fashion influencer profiles, which is reflected in the relatively low proportion of those who made their purchases based solely on their recommendations. Most respondents believe that fashion influencers only partially show a realistic resemblance to the fashion industry, which indicates moderate criticism and scepticism toward their representation.

Nevertheless, respondents regularly buy textiles online, mainly for practical reasons, i.e. greater choice and ease of purchase. Sustainability is also important in their purchasing decisions.

We are aware of the limitations of the research, which is a result of the unrepresentative sample, as it concerns students from a specific school and programme, and friends on social networks, mostly in a limited geographical area of Slovenia.

These findings provide comprehensive insight into respondents' behaviour and preferences in the digital environment, which is valuable for designing online marketing strategies and adapting fashion product offerings. New questions are being raised that can form the basis for new research, e.g. what are the differences between genders, are there noticeable differences in the influence between those who buy fashion products online and in brick-and-mortar stores, how do different social networks affect pur-

9 <https://wsj.westsciences.com/index.php/wsis/article/view/317#:~:text=locations,percent%20of%20users%20preferred%20partnerships>

10 <https://www.surveymonkey.com/curiosity/gen-z-social-media-and-shopping-habits/>

chasing behaviour, what are the differences between micro and regular fashion influencers etc.

Data availability statement: From 19 November 2025, the research data are available at <https://zenodo.org/records/17653857>.

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Design and Development of Comfortable Cut-Protective Workwear: A Review

Oblikovanje in razvoj udobnih delovnih oblačil za protiurezno zaščito: pregled

Scientific review/Pregledni znanstveni članek

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Abstract

The challenge of developing cut-protective clothing that ensures wearer safety and comfort remains complex in protective textile engineering. Traditional designs often compromise comfort for mechanical protection, leading to decreased wearer compliance and productivity. This review critically examines the interplay between comfort and cut resistance in the designing of protective apparel for industrial workers. Recent advancements in fibre science, yarn engineering and fabric architecture are highlighted for optimizing performance. This review begins by analysing the prevalence and causes of occupational cut injuries to establish functional requirements for protective clothing. It then explores how fibre type, yarn configuration and fabric structure impact cut resistance and comfort. Standardized test methods for evaluating cut resistance are discussed to provide context for material performance. Additionally, the review outlines garment design strategies that incorporate ergonomic principles to enhance mobility, reduce heat stress and improve user acceptability. It concludes with an outlook on emerging technologies such as smart textiles and 3D body scanning that could revolutionize future cut-protective workwear design.

Keywords: protective clothing, textile structure, clothing design, cut hazard, ergonomic comfort

Izvleček

Razvijanje zaščitnih oblačil proti urezninam, ki hkrati zagotavljajo varnost in udobje uporabnika, ostaja kompleksen izziv v načrtovanju in izdelavi zaščitnih tekstilij. Pri tradicionalno oblikovanih zaščitnih oblačilih je udobje pogosto žrtvovano v prid mehanske zaščite, to pa vodi v zmanjšano upoštevanje varnostnih ukrepov ter nižjo učinkovitost uporabnikov. Članek kritično analizira medsebojno povezavo med udobjem in odpornostjo proti urezu pri oblikovanju zaščitnih oblačil za industrijske delavce. Poseben poudarek je na najnovejših dosežkih na področju znanosti o vlaknih, tehnologiji prediva ter zgradbi tkanin, ki prispevajo k optimizaciji zmogljivosti oblačil. Študija se začne z analizo pogostosti in vzrokov delovnih poškodb zaradi ureza, da se določijo funkcionalne zahteve za zaščitna oblačila. Sledi raziskava vpliva vrste vlaken, konfiguracije prediva



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in strukture tkanin na odpornost proti urezu ter udobje. Obravnavane so standardizirane metode testiranja odpornosti proti urezu, ki omogočajo oceno zmogljivosti materialov. Prispevek opisuje tudi strategije oblikovanja oblačil, ki vključujejo ergonomska načela za izboljšanje mobilnosti, zmanjšanje toplotnega stresa in povečanje sprejemljivosti med uporabniki. Povzetek se zaključí z vpogledom v nastajajoče tehnologije, kot so pametne tekstilije in 3D skeniranje telesa, ki bi lahko v prihodnje močno vplivale na oblikovanje delovnih oblačil za protiurezno zaščito.

Ključne besede: zaščitna oblačila, struktura tekstilij, oblikovanje oblačil, nevarnost ureza, ergonomsko udobje

1 Introduction

Design plays a crucial role in gaining approval from observers and potential customers for popular daily apparel. Humans respond to visual information, including clothing and other everyday items. Clothing serves the fundamental purposes of modesty and safety, with beauty becoming increasingly important. The protective clothing market is shifting its focus towards emphasizing safety as its primary purpose, with protective textiles being developed to safeguard workers from a range of hazards. However, the performance of protective textiles may be limited by the need to meet safety standards [1, 2]. Occupational safety is a global concern, with millions of workers facing risks in various industries. The International Labour Organization (ILO) reports over 317 million work-related injuries annually, leading to more than 320,000 fatalities and significant human and economic costs [3]. The protective gear, such as stab-proof suits, cut-resistant aprons and gloves, is intended to minimize the chances of injury and offer protection from different dangers. It is important for individuals working in high-risk environments to wear appropriate protective gear to minimize the potential for harm [4–6]. These advancements are designed to improve the human body's ability to withstand or completely avoid injuries caused by sharp objects and other dangerous impacts [7, 8]. However, traditional protective options such as leather clothing, wire mesh steel, and steel gloves have faced various challenges, such as discomfort, reduced flexibility and inadequate protection [9].

Safety in the workplace is a top priority in industries such construction, manufacturing and logistics, where employees face risks from tools, machinery and materials. Cut-resistant workwear is essential for preventing injuries, protecting workers and meeting safety standards. Although current protective clothing offers good safety features, it often overlooks the importance of comfort, ergonomics and ease of wear. This can make it difficult for workers to follow safety protocols and stay productive [10]. Wearing larger and denser cut-protective suits can raise the energy expenditure of activities by 20% [11, 12]. This can lead to significant stress on the body when working, particularly in humid environments, resulting in cognitive impairment, discomfort, fatigue, reduced operational efficiency and potential harm [13]. The regulation of human body temperature relies on heat transport within the body and between the human body and its environment [14, 15]. When the body's heat regulation mechanisms are overwhelmed and heat accumulates, the core temperature can rise dangerously resulting in heat stress, which poses a significant risk to health and performance in various industrial settings [16]. Factors such as ambient temperature, physical activity levels and clothing choices play a crucial role in the development of heat stress-related illnesses [17]. Understanding these factors and their underlying principles is essential for assessing the risk of heat stress. The importance of wearer health is increasingly recognized in the use of cut-resistant gear [18–23]. To address this,

companies must focus on developing more comfortable and breathable protective workwear that can be worn in all types of weather conditions. Additionally, training programmes should be implemented to raise awareness about the importance of wearing protective gear and the potential risks of not doing so. By prioritizing employee safety and comfort, companies can create a safer work environment and reduce the risk of workplace accidents [24]. The process of creating cut-protective workwear is based on and tailored to the specific requirements of the user. These requirements are influenced by the user's work environment and the tasks they undertake, aiming to enhance both comfort and performance. Cut-protective workwear is an essential part of personal protective equipment (PPE) in various industries such as manufacturing, construction, healthcare and emergency services, where workers are exposed to risks from sharp tools, machinery or hazardous materials. While there have been significant improvements in enhancing the protective features of such clothing, the importance of comfort is often overlooked. Workers are more likely to wear protective gear consistently if it allows them to work without hindrance, discomfort or fatigue. Balancing comfort and protection is a complex challenge that involves integrating material science, ergonomic design and user-centred innovation. Protective clothing must meet strict safety standards for cut resistance while also providing breathability, flexibility and a proper fit. As the focus on worker well-being grows, there is rising demand for workwear that focuses on safety and comfort. This review aims to explore current advancements, challenges and research gaps in designing comfortable cut-protective workwear. It discusses the latest materials, design principles and technologies used to improve functionality and user experience. Additionally, it sheds light on the changing needs of industries and workers, offering insights into future directions for innovation in this field.

2 Cut and slash incidents in the workplaces

Preventing cuts is vital for workplace safety. Every year, numerous work-related accidents occur globally that could be prevented using proper protective equipment. Cuts and scratches are common injuries that can easily be prevented. Although statistics may differ, cuts and scratches are consistently listed as the second or third most common workplace accidents. These injuries account for approximately 30% of all industrial accidents, with hands and thumbs involved in about 70% of these cases. This has led to the development of protective gloves and sleeves [25]. Cutting hazards are prevalent in various industries. Incidents of cuts and wounds occur at a rate of 8.1 per 10,000 workers. Despite wearing cut-resistant gloves, an employee at an automobile production factory's pressing workshop sustained a thumb injury when a stainless-steel sheet slipped from his grip. While workstations may vary, the risks associated with cuts remain consistent. In industries where glass sheets are handled, hand and arm injuries are common during carrying and moving tasks. Forestry workers using chainsaws often require full-body protection, with minimal emphasis on hand protection. Electronics assembly and handling also pose cut risks to workers. Workers in food-processing plants and busy kitchen environments are at high risk of cut injuries due to the use of sharp equipment. Glass containers can crack or burst due to defects, necessitating the use of cut-resistant gloves when handling them. Textile factory operators face cutting hazards from vibrating threads in spinning processes. Hockey players risk neck cuts from extremely sharp skate blades, with some opting to forego neck guards despite the potential for injury. Workers must be aware of and take precautions against these cutting hazards to prevent injuries [26].

2.1 Fundamental requirements of cut-protective workwear

The term cut-resistant refers to a material's ability to withstand cuts, as tested by standardized methods while the term cut-protective encompasses all aspects of protection against cuts, not just cut resistance. It is important to use these terms accurately when selecting safety gear to ensure realistic expectations for workplace safety. Cut-resistant focuses on a material's ability to resist cuts, while cut-protective considers overall protection against cuts. Cut-resistant reduces the risk of cuts but does not guarantee absolute prevention, while cut-protective includes all protective features. Cut-resistant is rated by standards such as EN 388, ANSI/ISEA 105 and ISO 13997, while cut-protective may reference cut resistance as one component of protection.

Cut-protective clothing prioritizes practical functionality, thermal comfort and human movement to create a safe and comfortable micro-environment for the wearer. This clothing system acts as a barrier to protect the human body from potential hazards. In essence, cut-protective apparel serves three main purposes: protecting the user from cut and slash risks, providing psychological relaxation through sensual and thermal comfort, and enabling human movement during various activities. High-performance textiles composed of fibres, yarns, fabrics and composite components made from inorganic and functional organic polymers exhibit exceptional properties and qualities. UHMWPE provides exceptional cut resistance but has poor heat resistance, with a maximum continuous use temperature typically below 100 °C and a melting point of around 150 °C. For applications requiring both high cut and high heat resistance, aramid fibres such as Kevlar are the better choice, as they maintain their properties at temperatures exceeding 200 °C and do not melt. These fibres are commonly used in cut-protective clothing structures. Textile materials used in cut-protective clothing possess key mechanical attributes such as tensile strength, modulus, abrasion resistance, puncture resistance,

flame resistance, thermal and electrical insulation properties, heat resistance, chemical resistance, liquid absorption and dispersion properties, and protection against high levels of radiation. These properties are integrated into a single protective gear system to ensure adequate protection and comfort in different weather conditions [27].

3 Material selection for cut-protective workwear

3.1 Selection of fibre

Functional clothing, such as activewear, innerwear and protective workwear, utilizes a variety of natural and synthetic fibres with distinct properties. The choice between natural and synthetic fibre depends on the intended level of physical activity. Natural fibres are hydrophilic and suitable for low activity levels, while synthetic fibres are hydrophobic and preferred for high activity levels. Hydrophilic fibres quickly absorb moisture due to their higher surface energy, while hydrophobic fibres resist moisture absorption due to their lower surface energy [28]. The cut-resistance functionality and comfort of clothing are greatly influenced by the characteristics of the chosen fibre components [29]. It is crucial to carefully choose fibre components with various anti-cutting capabilities for different operating conditions. Workers in conventional factories were provided with protective clothes made from cut-resistant textiles, which mostly consisted of natural fibres and synthetic fibres such as cotton, hemp, polyester and spandex. Cut-resistant clothing composed of conventional natural fibre content has poor safeguarding properties due to inadequate mechanical and outdoor resistance, which restricts their utilization in various safety gear industries. However, due to their high utilization rate, lightweight, versatility and low cost, they are still a frequently used protective material in factory manufacturing situations [30–32]. Natural fibres exhibit the strength and stiffness typical of most fibres, have a low specific gravity and demonstrate improved elasticity and extensibility.

When integrated into protective textiles, it improves wearer comfort and offers greater strength and durability than natural fibres. Furthermore, it is affordable and incredibly cost-efficient. While natural fibres and synthetic fibres offer numerous benefits, they also possess significant drawbacks. For instance, cotton fabrics exhibit limited elasticity, are prone to shrinking and distorting after washing, and lack resistance to acid. Similarly, hemp fabrics have a coarse texture and tend to develop burrs when in direct contact with the body, resulting in a less smooth and comfortable experience. The truncated fibres generated during the processing and shaping of synthetic fibres have detrimental effects on the skin and respiratory system of personnel. In addition, conventional cut-resistant fibre materials lack effective protection and fail to meet the safety criteria for people's work activities. To enhance the competitiveness of both natural and synthetic fibres, it is crucial to modify and enhance their value in

usage [33, 34]. Conventional fibres such as cotton, polyester, nylon and wool are being blended with HPPE or aramid to develop cut-resistant materials. High-performance fibre has progressively displaced conventional fibre components for cut-resistant clothes due to its superior mechanical strength, excellent heat retention and anti-abrasion properties. Currently, aramid 1414, ultra-high molecular weight polyethylene fibre, p-benzoxazole polyester fibre, glass fibre, metal fibre and other high-performance fibres are commonly employed as barrier components in factory manufacturing workflows for cut-protective clothing. Using physical and chemical techniques, some researchers have enhanced the cutting capability of fibres or yarns. For example, Jeffrey CM employed a lab-scale wet spinning experimental approach to generate aramid copolymer fibres used in cut prevention [35]. Table 1 provides an overview of the characteristics of the major high-performance fibres used in cut-resistant textiles.

Table 1: Overview of properties of major high-performance fibre [36].

Fibre	Diameter (μm)	Strain (%)	Density (g/cm^3)	Tensile stress (GPa)	Modulus of elasticity (GPa)
Para aramid	13.0	3.3	1.44	3.31	94
UHMWPE	18.8	3.6	0.98	2.62	88
PBO	12.3	3.5	1.54	5.80	180
Aromatic polyester	23.5	3.3	1.41	3.20	75
Glass	5.5-9.3	5.5	2.48	4.80	85

DSM introduced Dyneema Diamond Technology in 2006 to improve its unique properties. This technology combines HPPE (high-performance polyethylene) filled with a micro-sized, cut-resistant inorganic filler to create a composite material [37]. The fibre produced using Dyneema Diamond Technology, as shown in Figure 1, has a distinct morphology. By incorporating an inorganic filler, this technology significantly boosts the cut resistance of the fibre compared to traditional HPPE fibre. According to DSM's data, Dyneema Diamond

Technology offers a 200% increase in cut resistance over standard Dyneema fibre [38]. The addition of extraneous material complicates the process of fibre spinning. Superdrawing is essential for achieving a significantly elevated level of alignment and crystalline structure, allowing for the exceptional stiffness and strength of HPPE fibre. However, the addition of inorganic filler substantially increases the difficulty of superdrawing and has a significant impact on spinnability. The fibre's strength decreased by over 50% [39].

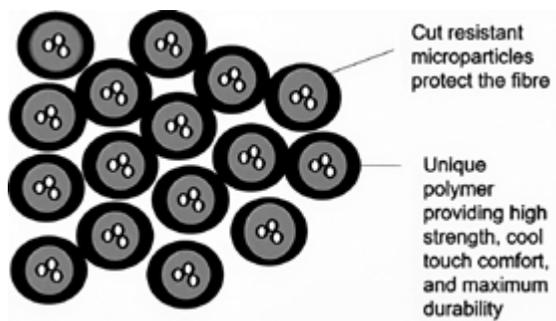


Figure 1: Microscopic composition of a fibre utilizing the Dyneema Diamond Technology

Indeed, the utilization of hard filler to enhance cut resistance in thermoplastic fibre is not a novel concept. In the 1990s, Hoechst Celanese submitted patent applications for the utilization of inorganic fillers or fibres to enhance the cut resistance of fibres [40–47]. The patents explicitly describe the use of tungsten and aluminium oxide, which resulted in an improvement in cut resistance of over 300% according to a certain cut-testing method. The addition of alumina to para-aramid fibre to increase cut resistance was also revealed in another patent [48]. The cut resistance was increased by 15% with 0.5% by weight of alumina in the fibre, without compromising tenacity.

3.1.1 Function of fibre structure

Fibres of different cross-sectional shapes are being used in functional clothing due to their ability to transfer heat, moisture and liquids through fabrics effectively. The inclusion of non-circular fibre profiles increases the fibre's shape factor. This, in turn, affects the capillary gaps between fibres, the spaces between yarns, the density of packing, the specific surface area and, ultimately, the thermo-physiological properties of fabrics [49,50]. Fibres that have a higher specific surface area exhibit excellent moisture absorption and release properties. The presence of micro grooves on the surface of the fibre increases its ability to absorb liquid by capillary action. This allows moisture to be drawn in and then spread out over the surface of the fibre, facilitating its dissipa-

tion [51]. Various fibres and their cross-sections are frequently utilized in functional clothing. Hollow fibres and fibres with varying sizes of grooves are commonly used in activewear, sportswear and clothing that is worn next to the skin to achieve favourable thermal insulation characteristics. Hollow fibres have a significant trapped air volume, leading to enhanced thermal insulation properties in fabrics or garments made of these fibres. Thermolite fabrics with improved thermal insulation and wicking properties are produced using hollow core fibres with twisted or convoluted surfaces [52]. The formation of irregular capillaries occurs when cotton fibres are embedded within the yarn, inhibiting fluid flow due to the flat, lima bean-shaped cross-section and ribbon-like appearance of the cotton fibre [53]. Introducing voids in the fibre core can enhance wicking and heat resistance. Welkey is a type of fibre that has a hollow core and a body with numerous tiny pores. The thermal resistance of fibres increases due to an increased amount of air gaps inside them. The capillary action, resulting from the formation of microscopic pores in the fibre body, enables sweat to be wicked away from the skin. Coolmax is a type of polyester fibre that has been altered and improved by Dupont. The fibre has a double scallop shape with four channels, providing 20% more surface area compared to regular polyester fibre. This results in improved wicking, moisture vapor permeability and water spreading over a larger area in the fabric [54–56]. Karaca et al. conducted a study comparing the thermal comfort properties of fabrics made from polyester fibres with different cross-sectional shapes. They observed that fabrics made from hollow fibres had low thermal insulation, air permeability, and water vapor permeability. On the other hand, fabrics made from trilobal polyester fibres had higher air and water vapour permeability and lower thermal conductivity compared to fabrics made from round fibres [57]. According to Behera and Singh, the physical properties and tactile characteristics of polyester multifilament yarn fabric were modified when the form of the filaments was changed [58].

Table 2: Role of fibre parameters on different attributes of clothing

Fibre parameter	Performance attributes	Aesthetic attributes	Tactile attributes	Wearing comfort attributes
Strength, fineness, cross-sectional shape, maturity	Tensile strength, tear strength, bursting strength, abrasion resistance, crease resistance	Surface texture, lustre, fancy effect, handle, drape	Compression, friction, shear, bending rigidity	Stretchiness, lightness, slip-ability, reduction in clinging, prickliness

Varshney et al. conducted a study on the impact of polyester profile on the physiological characteristics of polyester fabrics. They found that noncircular fibres increased the volume of the fabric, resulting in a higher mass flow rate and greater resistance to heat flow [59]. Wang et al. compared monofilament yarns with a circular cross-section to those with a five leaf cross-section. They found that, at the same twist level, the fibres with a five leaf cross-section formed five beads along the length of the fibre and had a greater number of capillaries in the yarn than conventional yarns made with circular cross-section fibres. The wicking height of five leaf yarns was found to be greater than that of ordinary yarns [60]. The role of fibre parameters is also summarized in Table 2.

3.2 Selection of yarn

The selection of yarn is closely linked to the desired characteristics of the fabric. The choice of compound yarns is crucial in producing pleasant cut-protective fabric. Compound yarns are formed by intertwining many types of fibres or yarns, merging the advantageous characteristics of each constituent. This leads designers to produce cut-protective clothing with higher performance characteristics, including strength, flexibility and abrasion resistance, which are critical for cut prevention, by intelligently selecting the types of fibres and arranging them in the compound yarn. Compound yarn is generally prepared by using core spun and wrap spun processes. The staple spun yarn spinning technique yields core spun yarn [61]. In the spinning process, the core is introduced into the roving, which is then twisted around the core. Over time, the primary thread gradually forms a protective covering that encases

the central part. The core can be made of either spun yarn or filament yarn in practice. However, in practice, the core is typically made of filament yarn, such as steel, glass, spandex or the monofilament of organic fibre-like polyester. The sheath must still be made of staple spun yarn. Typically, a sheath composed of staple spun yarn adequately conceals the core, making it difficult to perceive from the outside. Wrap yarn is alternatively referred to as spin-covered yarn. The process involves the continual wrapping or twisting of yarn around a core yarn, which can be either a monofilament or multifilament yarn, or a staple spun yarn. Wrap spinning uses a hollow spindle to make this sort of yarn [62–69].

The core is often located in the inner layer of the yarn and gives special bulk qualities such as remarkable strength (e.g. polyester or nylon filament) or high flexibility (e.g. rubber or spandex). To eliminate fibre separation or core sliding, the sheath or yarn wrap should have a solid hold on the core. It should also insulate the main filament from outside influences. This is especially critical if the core filament is elastomeric (e.g. rubber or spandex), as these filaments can disintegrate when exposed to a variety of chemicals or UV radiation. Furthermore, the wrap that comes into touch with the user should have comfort features including softness, flexibility and porosity. The wrap yarn can be either spun or filament. Two wrap yarns may be used in some circumstances, with one twisted in the opposite direction to the other, resulting in unique appearance effects and an appropriate equilibrium towards unwanted yarn sneering. The combination of various fibre types in compound yarns enables the attainment of desired performance levels while simultaneously reducing

weight. Compound yarns are frequently preferred due to their enhanced comfort and safety protection to meet the requirements of mobility and agility in cut-protective gear for industrial or sports use.

3.2.1 Influence of yarn structural properties

The characteristics of fabrics are influenced by several yarn variables, such as yarn twist, yarn count, yarn spinning system and yarn types. Modifications in any of these characteristics ultimately result in alterations to the yarn's structure which, in turn, is influenced by the geometry of the fibres. The arrangement of fibres in yarn determines the heat

and moisture transport characteristics of fabrics. The versatile nature of yarn structure allows for capillary flow, which can result in lateral tension that impacts the size of capillaries as the liquid rises. The disruption of the continuity, length and orientation of the capillaries is caused by variations in the packing density inside the yarn structure. The variation in pore size, shape and orientation has an impact on how liquid enters the structure of the yarn and, consequently, its ability to retain liquid. The role of yarn parameters and yarn type on the different attributes is presented in Tables 3 and 4.

Table 3: Role of yarn type on the structural and expected properties

Yarn type	Structural attributes	Expected features
Spun yarn	<ul style="list-style-type: none"> - hairy surface - random fibre arrangement - variability in count and diameter - presence of imperfections 	<ul style="list-style-type: none"> - textured or "spun" appearance - soft and warm hand feel - greater bulkiness than combed yarn
Bulk yarn	<ul style="list-style-type: none"> - high volume - low fibre packing density 	<ul style="list-style-type: none"> - lofty and soft texture - textured appearance - hairy surface similar to spun yarn
Stretch yarn	<ul style="list-style-type: none"> - filament core with staple fibre sheath 	<ul style="list-style-type: none"> - high stretchability - enhanced comfort and fit
Filament yarn	<ul style="list-style-type: none"> - maximum fibre alignment - high uniformity - dense filament packing 	<ul style="list-style-type: none"> - lustrous and smooth appearance - high sheen - soft handle - low bulk and covering power - limited potential for intimate fibre blending
Textured yarn	<ul style="list-style-type: none"> - combines features of both spun and filament yarns - high degree of fibre disorder (crimps, loops, coils) - uniform yarn count and diameter - low fibre packing density - increased surface area and air entrapment 	<ul style="list-style-type: none"> - highly textured and voluminous appearance - enhanced bulk and softness - improved covering power and opacity - good elasticity and stretch - effective thermal insulation - moisture-wicking with low moisture retention - improved comfort and flexibility - resistance to wrinkling and creasing

Ozguney et al. explored the impact of yarn fineness on the comfort qualities of garments created from it. They observed that the bending stiffness and compression of textiles made from increased linear density yarns are greater than those made using reduced linear density yarns [70]. An increase in yarn coarseness improves all of the fabric's low-stress mechanical properties. Raj and Sreenivasan's studies

on various cotton textiles reported that increasing yarn count, twist and giving a thinner construction enhances the fabric's air permeability [71]. Ozdil and fellow researchers evaluated the influence of twist number and yarn count on the performance of rib cotton textiles. Their research reveals that when linear density declines, so do yarn diameter and fabric thickness. These standard yields decreased heat

Table 4: Role of yarn structural parameters on the different attributes of clothing

Yarn structural parameter	Performance attributes	Aesthetic attributes	Tactile attributes	Wearing comfort attributes
Yarn count	Tensile strength, tear strength, bursting strength, abrasion resistance	Surface texture, lustre	Handle, drape	Lightness, stretchiness
Yarn twist	Tensile strength, crease resistance, abrasion resistance	Surface texture, fancy effects	Compression, bending rigidity	Slip-ability, reduction in clinging
Yarn hairiness	Abrasion resistance, pilling tendency	Surface texture, dullness	Prickliness, handle	Air permeability, reduction in clinging
Yarn evenness	Uniformity in strength, reduced weak spots	Smoothness, visual uniformity	Consistent handle	Consistent comfort, reduced irritation
Yarn blending ratio	Balance of mechanical properties, durability	Colour effects, lustre variation	Handle, drape	Moisture management, thermal regulation
Yarn bending rigidity	Crease resistance, dimensional stability	Drape, form retention	Bending rigidity, handle	Flexibility, ease of movement
Packing co-efficient	Tensile strength, abrasion resistance, bursting strength	Bulk, opacity	Compression, surface feel	Thermal insulation, reduction in clinging

insulation and thermal conductivity while increasing water vapor permeation. As a result, textiles made of finer yarns have a warmth sensation and reduced heat absorption. Water vapor permeability and thermal absorptivity rise as the twist number of the yarns increases, resulting in decreased thermal resistance and a cooler sensation. They also demonstrated that combed cotton yarn knitted textiles had greater thermal conductivity, thermal absorptivity and water vapor permeability than carded cotton yarn knitted clothing. As a result, combed yarn textiles are more comfortable than carded yarn fabrics [72]. Aliouche and Viallier investigated the hairiness qualities of yarns. They demonstrated the importance of hairy appearance on tactile sensations such as roughness on the exterior, fabric compression and handling [73]. There has been various research on the wicking characteristics of yarns and textiles as an essential criterion [74-79]. Wicking is a need for clothing permeability. Asayesh and Maroufi investigated the effect of yarn rotation on the wicking ability of cotton interlaced weft knitted fabric. A higher yarn twist number in such fabrics results in reduced wick-

ing ability [80]. Wickwire et al. discovered that while slack clothing reduces the efficiency of transporting moisture and perspiration away from the skin, it may improve the wearer's comfort, regardless of its ability to wick moisture away [81].

3.3 Selection of woven fabric

The selection of weave patterns impacts the fabric's flexibility and drape. It is crucial to acknowledge that the selection of weave structure is contingent upon the particular demands of the application. Although satin weave has benefits in terms of comfort and cut protection, different weave structures may be better suited for situations where criteria such as durability, rigidity or breathability are the main considerations listed in Table 5. Weaves with more aperture, such as plain weave or leno weave, exhibit increased flexibility and improved drape ability, thus boosting wearer comfort through unrestricted mobility. The satin design was selected due to its tight structure with fewer interlaces compared to other weaves such as plain or twill weave. This tightness improves the fabric's resistance to cuts by minimizing the

areas where a blade can penetrate. The satin weave produces a silky, shiny surface that feels smooth and cozy against the skin. This is especially advantageous for cut-protective fabric when worn close to the body since it reduces irritation and pain after extended periods. Cut resistance changes in fabrics depending on the cutting angle of the blade, cutting speed and the fabric surface roughness. With an increase in yarn linear density, a woven fabric's surface roughness and frictional resistance increase [82]. The amount of frictional force generated also depends on the surface roughness of the fabric. Ajayi. J. O. and Elder. H. M in their research found that the surface roughness and frictional resistance of a woven fabric increase with an increase in the yarn's linear density. This was due to the increased yarn crown height which caused the mechanical interlocking of crowns during any movement [83]. In addition to meeting

the demands for cut resistance, composite materials and hybrid architectures are frequently used. Cut-resistant clothing employs combination cord threads that include stainless steel filaments as the core and other high-performance fibres as the sheath to offer versatility and cut protection [84]. The conventional protective clothing for chainsaw employees comprises trousers and chaps that typically have an exterior material made of nylon, polyester or denim, and inner inserts made of layers of ballistic nylon or high-tenacity polyester fabric, while higher-quality apparel comprises layers of aramid fabric such as Kevlar® or ultra-high molecular weight polyethylene (UHMWPE) such as Dyneema. The cut-resistant safeguards offer minimal protection to the user and are intended to block the chainsaw driving sprocket, preventing the cutting blade from slashing through the trousers [85].

Table 5: Role of weave structure on general attributes of clothing

Weave type	Interlacing pattern	General character
Plain	<ul style="list-style-type: none"> - each warp yarn interlaces with each weft yarn in an alternate sequence - no distinctive design; can use contrasting colours 	<ul style="list-style-type: none"> - maximum number of interlacements per unit area (balanced or unbalanced) - tends to wrinkle the most - may feel sleazy if sett is low - least absorbent among basic weaves - simple, firm and durable structure
Twill	<ul style="list-style-type: none"> - warp or weft yarns float over two or more yarns in a regular progression to either to the right (z) or left (s) 	<ul style="list-style-type: none"> - characteristic diagonal lines (s or z twill) - fewer interlacements than plain weave - wrinkles less than plain weave - strong, firm texture - enhanced tear strength - can be woven at higher setts (densities)
Satin	<ul style="list-style-type: none"> - warp or weft yarns float over four or more yarns in a staggered progression, creating a smooth surface 	<ul style="list-style-type: none"> - very few interlacements; long floats - flat, smooth, and highly lustrous surface - maximum drapability - high sett possible - prone to slippage and snagging due to long floats - luxurious appearance and feel

3.3.1 Role of fabric structural parameters

The thermo-physiological properties of clothing are affected by the structural factors and general characteristics of fabrics. Factors such as fabric structure, thickness, cover factor, aerial density, bulk density, fabric porosity and finishing treatments affect the heat and moisture management capabilities of

fabrics, ultimately defining their comfort properties. Woven fabrics are commonly used in outerwear, active wear, workwear and athletic attire. The level of air trapped inside different fabric structures varies due to differences in porosity, with knitted fabrics generally trapping more air than woven fabrics. Thermal insulation in fabrics is achieved through

the presence of fibres, creating air pockets that restrict air circulation and act as a barrier against heat loss through radiation [86]. Fabric with multiple spaces for stagnant air, such as pile or napped fabric constructions, exhibits enhanced thermal insulation properties. However, as the bulk density of the fabric increases, thermal insulation decreases, as heat can pass through more easily. Approximately 70% of a fabric's volume consists of trapped air, with fibre making up the remaining 30%. The characteristics of air primarily influence the transfer of heat through textile materials. Fabrics with fibres and strands brought to the surface, such as pile or napped fabric structures, provide enhanced thermal insulation [87, 88]. Differences in the amount of water carried by fabrics derive from variations in their fundamental material structure. The arrangement of fibres in yarn affects structural variances, impacting the roughness factor ($\cos \theta$) of the yarn and the size and continuity of capillaries. A haphazard distribution of fibres results in a greater contact angle, while a strong alignment of fibres leads to a lower contact angle, facilitating faster water movement in yarns and textiles. Sledzinska et al. conducted a study on the comfort attributes of work attire for employees with locomotor disabilities. They emphasized that overall comfort, including the design and choice of materials, is crucial for handicapped individuals. The test results indicated that twill 2/1 S fabrics with a surface mass of 243 g/m², 204 g/m² and 175 g/m² were the most viable options for developing work

attire for impaired employees [89]. Limeneh et al. conducted a study to examine the impact of different weave structures, specifically plain, twill and satin, on the comfort properties of fabrics. The researchers found that satin woven fabrics had the highest levels of water vapour permeability, water absorption rate and air permeability. Twill woven fabrics ranked second in these properties, while plain woven fabrics ranked third. Nevertheless, the heat resistance of plain-woven fabrics was found to be the highest, while the stiffness was the lowest for satin woven materials [90]. Tahvildar et al. examined the visual and tactile characteristics of worsted fabrics made with four different weave structures (plain, twill 2/1, twill 2/2 and hopsack 2/2) and four sets of yarns produced using different yarn-spinning methods (solo, siro, single-ply ring and two-ply ring). According to their suggestion, the fabric's open structure and the movement of threads within it enhanced its capacity to recover from creases, increased flexibility and improved air and water vapour permeability. However, the fabric's resistance to abrasion and pilling decreased. In addition, the researchers determined that the comfort and appearance characteristics of fabrics made from yarns spun using different spinning processes may be significantly influenced by the level of compactness and the position of fibres within the yarn structure [91]. The impact of fabric parameters on the different attributes of clothing is summarized in Table 6.

Table 6: The role of fabric parameters on the different attributes of clothing

Fabric parameter	Performance attributes	Aesthetic attributes	Tactile attributes	Wearing comfort attributes
Thread density, fabric thickness, weave type cover factor, bulk density, areal weight,	Tensile strength, tear strength, bursting strength, abrasion resistance, resistance	Surface texture, lustre, fancy effect, handle, drape	Compression, friction, shear, bending, rigidity	Stretchiness, lightness, slip-ability, reduction in clinging, prickliness

4 Standard methods for cut protection performance

The referenced articles identify three cut test standards, with each evaluation technique using a distinct testing apparatus. The specimen is placed on the specimen holder and under the blade in all but one of the three cases. Additionally, there are some similarities and differences between the ASTM and ISO procedures but these two, along with the EN 388, have fundamentally different tools and testing methods.

4.1 EN 388 (Europe): Protective gloves against mechanical risks

The EN evaluation method determines a material's cut resistance by measuring its response to the cutting action of a rotating circular blade. During testing, the specimen is placed under a load of 5 N, which is applied to the blade with minimal tension, as illustrated in Figure 2. The rotary blade used has a diameter of 45 mm, while the sample holder is a straight container measuring 90 mm in width and features five holes, each 5 mm wide, along its base. To ensure the accuracy and consistency of the blade, a standard cotton fabric is tested as a reference, both before and after the evaluation of each specimen [92]. The protective performance of the material is then quantified using the 'T' index, as detailed in Table 7.

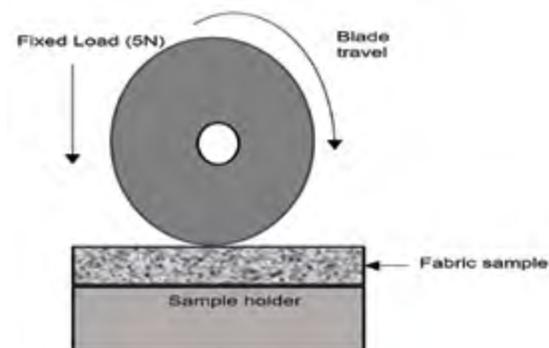


Figure 2: EN 388 (Europe) Coupe cut test

Table 7: Performance grading of cut protection clothing [93]

Cut protection level	Index "I"
Level 1	1.2
Level 2	2.5
Level 3	5.0
Level 4	10.0
Level 5	20.0

4.2 ASTM F1790 (USA): Standard test method for measuring cut resistance of materials used in protective clothing

The assessment is based on determining the force necessary to cut through the specimen after the square blade has traversed 20 mm, the current standard test distance in either direction. During testing, the rectangular blade moves at a constant speed of 150 mm/min in a single direction [94]. As shown in Figure 3, the upper section of the specimen holder is designed with a curved surface having a 38 mm radius. This curvature helps prevent misalignment between the sample surface and the blade. Cut resistance is calculated by analysing the relationship between applied load and displacement, as represented in the load-displacement curve [95].

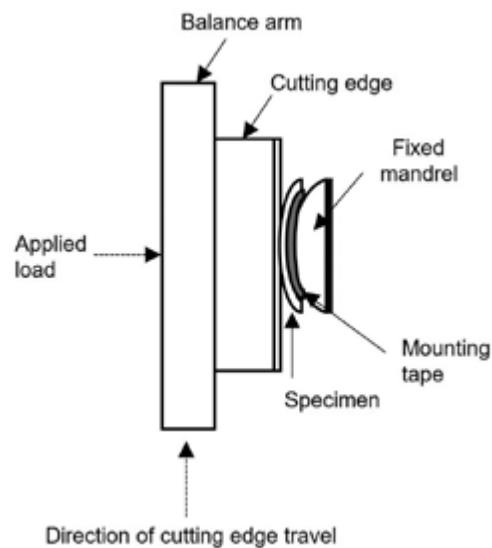


Figure 3: ASTM F1790-05 CPPT cut test

4.3 ISO 13997 (international): Protective clothing — Mechanical properties — Determination of resistance to cutting by sharp objects

Both ASTM F1790 and ISO 13997 standards use straight blades and angled specimen holders to evaluate cut resistance following similar testing principles. The cut-testing apparatus is illustrated below. During the test, the blade moves horizontally across the specimen at a controlled speed, while the primary measurement is the force required to achieve a cut [96]. This value serves as the key indicator of cut resistance, as shown in Figure 4. The standards also define different performance categories or regions, which are detailed in Table 8.

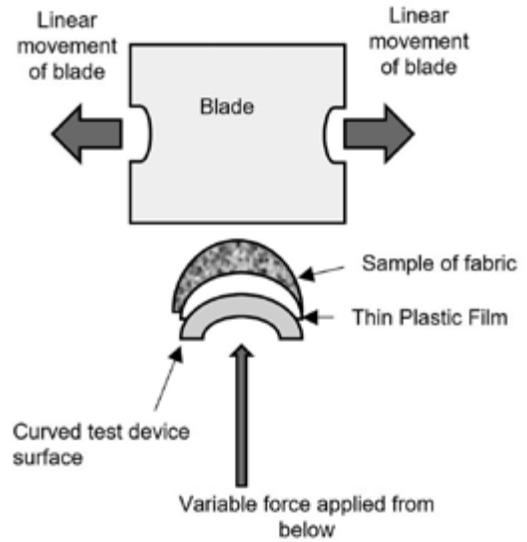


Figure 4: ISO 13997 (international) TDM cut test

Table 8: Different locations of ISO13997 and ASTM F1790 [97]

S. no.	ISO13997	ASTMF1790
1.	Constant normal force	The normal force is a variable that depends on the coefficient of friction of the materials.
2.	Consistent blade speed	Blade speed remains same.
3.	Calculate cut resistance for a 20mm blade displacement.	The cut resistance is determined by measuring the movement of the blade at a distance of 25 mm.
4.	Installation procedure: the sample is positioned on double-sided adhesive tape, ensuring direct contact with the conductive substance.	Installation process: the sample is affixed to double-sided tape. The blade must penetrate the sample material and the double phase tape to make contact with the conductive material.
5.	The process for correcting blade sharpness is as follows: the value of C is equal to 20 / l, where l represents the cutting stroke on neoprene at a force of 5N.	The process for correcting blade sharpness is as follows: the value of C is equal to 25 / l, where l represents the cutting stroke on neoprene at a force of 400 grams.

4.4 ISO 13998 (international): Protective clothing - Aprons, trousers and vests protecting against cuts and stabs caused by hand knives

Figure 5 depicts the apparatus used for impact cut resistance testing. In this setup, the test specimen is repeatedly struck by a standard knife blade mounted within a guided falling block. Upon release, the

block drops freely, allowing the blade to penetrate the sample positioned beneath it. The blade is fixed in the block so that it extends 40 mm below the holder. Additionally, the centre of gravity of the block-and-blade assembly is situated 65 mm above the blade tip. The combined mass of the block and blade is 1,000 grams [98].

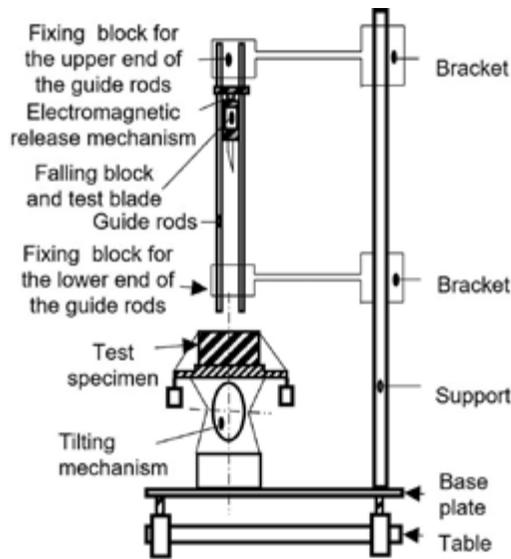


Figure 5: Schematic diagram of ISO13998 impact cut test

4.5 ISO 13999-3 (international): Protective clothing—gloves and arm guards designed to protect against cuts and stabs caused by hand knives—Part 3: Impact cut test for fabric, leather and other materials

This evaluation standard is designed solely for testing and is not intended to serve as a performance specification. The testing procedure closely follows the methodology outlined in ISO 13998. Figure 6 shows the apparatus used for knife impact penetra-

5 Trends regarding the growth of cut-protective workwear

The market for cut-protective workwear is experiencing robust growth, driven by several key trends related to safety regulations, technological advancements, evolving end-user demands and sustainability initiatives. Governments and regulatory bodies worldwide are enforcing more stringent safety standards, especially in high-risk industries. This has led to the increased adoption of cut-protective workwear to minimize workplace injuries and ensure compliance. Innovations in materials and

tion testing. The primary distinction lies in how the test specimen or glove is supported. In this method, the specimen is placed on a horizontal arm that terminates in a circular anvil with a central hole, through which the knife blade passes after free-falling. In contrast, the ISO 13998 method positions the specimen on an inclined plastic mass. The circular anvil in this setup features a convex top surface to support the specimen and a central rectangular slot that allows the blade to penetrate during testing [99].

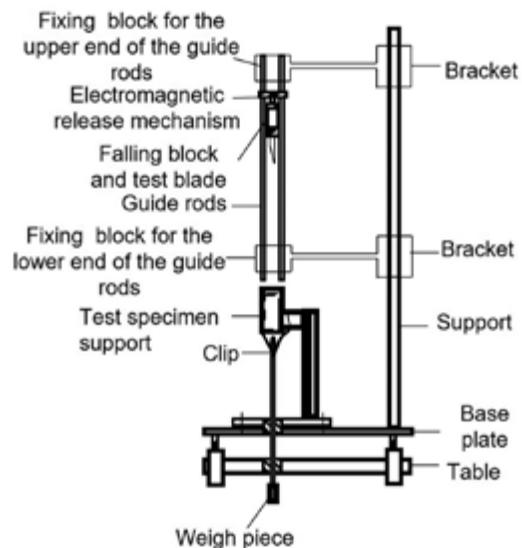


Figure 6: Schematic diagram of ISO13999-3 impact cut test

manufacturing processes are leading to the development of lighter, more comfortable and more durable cut-resistant garments. New fibres such as ultra-high molecular weight polyethylene (UHMWPE), aramids and engineered blends provide higher cut resistance without sacrificing dexterity or comfort. A lighter weight often provides the user with more comfort and dexterity, while greater cut resistance offers more protection. These two factors are often conflicting. Less material results in a lighter weight, which usually means reduced cut resistance. To address this challenge, innovative solutions must be developed. For example, in an extreme scenario, a very thin medical latex glove could offer strong cut

resistance, providing surgeons with more protection compared to conventional latex gloves without cut-protective function. There is a growing demand for workwear that offers protection against multiple hazards such as cuts, abrasions, impacts, chemicals and cold, while maintaining comfort and flexibility. High-visibility features are also increasingly integrated to enhance safety in low-light or high-traffic environments [100].

6 Designing of comfortable cut-protective workwear

People's daily lives cannot function without clothing, which also shapes how they view themselves. It can foster a well-being-promoting transdisciplinary functional approach. The development of pleasant and appealing goods that can benefit us in many parts of our everyday lives may be aided by good aesthetic and technological design, which is fuelled by relevant end-user research. With the addition of intelligent features, technological advancements are leveraged to improve the functionality of protective

garment systems. Functional cut-protective clothing gives the wearer access to unique features, such as help with monitoring and assessing possible risks that the user may encounter, which conventional protective equipment could not. An integrated approach for the development of functional protective textiles is shown in Figure 7.

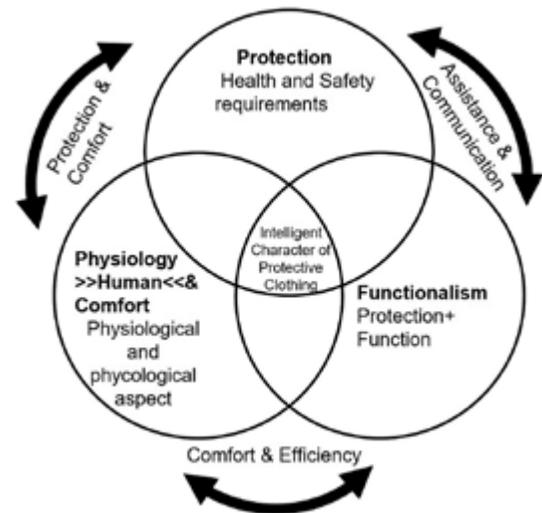


Figure 7: Integrated approach to functional protective textile [101]

6.1 Initiation of design process

The design process entails a sequence of methodical stages that must be adhered to before the actual production of the product. Dastoor conceptualized the process of manually designing [102]. The synthesis of a fabric structure involves a step-by-step process that starts with the main design goal and progresses through many sub tasks in a top-down manner. The designer selects the type of fibre for interlacing yarns, considering factors such as cost and physical properties, based on the limitations of the property. The specified tensile strength of the cloth thereafter determines the yarn count. The precise modification of yarn characteristics is achieved by changing the twist of the yarn, followed by adjusting the density of the yarn in terms of the number of ends and picks per inch. The choice of fabric weave is determined by factors such as tearing strength, thickness, fluid

permeability, etc. Hearle states that in a conventional process, the current design is altered by incorporating expert opinions regarding fabric samples and/or consumer feedback about a fabric or product [103]. The incorporation of macro-mechanics, which examines the relationship between fabric performance and fabric properties, and micro-mechanics, which explores the connection between fabric construction and fibre, yarn and fabric properties, has become an integral component of contemporary design procedures. Matsuo introduced the concept of FASE (Fibre Assembly Structural Engineering) as a method for creating textile products. FASE is a type of knowledge system that focuses on configuration, structure and phenomenology [104]. According to the author's perspective, the design process should begin by acknowledging requirements and then proceed with the sequential steps.

6.2 Steps in designing comfortable cut-protective workwear

Functional clothing is primarily constructed from technological textile materials. However, it is crucial to combine high-tech materials with similarly cutting-edge procedures and techniques for garment design and production to fully utilize the unique functions that they provide. Improved cutting, stitching and connecting techniques are required to handle and transform novel materials into performance clothing systems. Each of these phases influences the final appearance, fit, comfort and functionality of a piece of clothing [106].

6.3 Measurement of body dimensions and sizing

The initial stage in clothing design is generally to create body measurements of the desired end users. The conventional size chart cannot be used in designing cut-protective clothing since it depends on traditional anthropometry. Data provide measures that show size but provide no information on the complicated human body shape incurvature or postures. Ergonomic block creation necessitates the collection of 3D anthropometric data in a variety of realistic poses. 3D body scanners may be used to acquire form, size and posture data from the population in both static and dynamic modes. Ergonomic measurements, such as range of motion, must also be gathered and considered while developing. Human motion analysis systems are used to understand the changing body shape of clothing during specific activities.

6.4 Pattern engineering

Pattern creation is a multi-step process based on a trial-and-error method. To obtain the proper fit and performance, the 3D-2D-3D procedure necessitates a significant amount of tweaking, modification or fitting. Cut-protective clothing should be created based on an approach that precisely reflects the shape of human beings, regardless of whether in a stable manner or an energetic form during labour

and movement. As a result, the traditional pattern technique that relies on basic front/back/sleeve panels is limiting. Ergonomic clothing design shapes must correspond to the user's size and posture while matching the 3D shape and function of the individual's body [107–110]. Therefore, cut-protective clothing designs are developed in 3D, for example on the body directly. Furthermore, cut-protective workwear would require the "zoning" of patterns, such as using spacer fabric for thermal insulation or durability against impacts in the upper body region, etc. To allow for the use of multiple components in a block, pattern blocks are constructed in new ways. Patterns must be designed for ergonomic purposes based on body movement to provide greater mobility and reach areas that experience strain during strenuous activities (crotch, underarm, knee and elbow). It is essential to develop articulated knee and elbow designs. Pattern formations are produced directly from a three-dimensional image of a moving body, responding to external properties as required. Flattening these selected 3D areas results in 2D patterns. Fabric mechanical characteristics can be considered in the 3D pattern, and a coloured simulation of the deformation stresses and strains may be visible while the garment is being worn.

6.5 Assembly of clothing components

The process of selecting the design and dimensions of each two-dimensional template that will ultimately be linked to form a 3D shell is known as pattern engineering. After creating these designs, they must be cut, constructed, and linked. They must also be linked with the methods of removing and putting back the clothing (buttons, closures and buckles), as well as any additional components that make up a complete garment assembly. The user's activities, position and working environment, along with the qualities of the materials employed, determine pattern design and link it with assembly processes (sewing, attachment and fusing). Multiple fabric panels with various characteristics must be assembled using advanced handling procedures. Seams that are tradi-

tionally sewn can occasionally damage the integrity and functionality of manufactured garments. The cut-protective areas in protective clothing are shown in Figure 8.

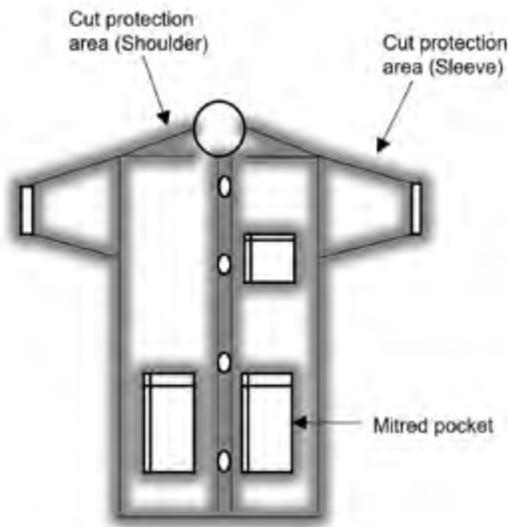


Figure 8: Cut-protective areas in protective clothing [111]

These systems are usually constructed using bonded stitches, welding (high frequency, ultrasonic and laser) and bonding with adhesive. A third approach utilized in contoured garments for body contouring and support is 3D moulding. As a result of these changes, new-age clothing appears cleaner, fits better, and is lighter in weight and less bulky.

6.6 Role of clothing design on ergonomic wear comfort

Cut-protective clothing requires ergonomic comfort to assist the wearer throughout diverse tasks. The most significant characteristics of ergonomic wear that clothing should meet are the flexibility of mobility, load/strain reduction and physical shape preservation [112, 113]. These are primarily defined by the fit design and pattern structure of the garment, and may be modified by the flexibility or stretchability of the material [114]. Psychological factors demand that the structural properties of clothing correspond to the movement, degree of equality, length of mobility,

force and individual joint movement. The majority of the elements that influence this include the shape and fit of the clothes in relation to the body structure and the pressure and abrasion caused by the clothing on the human structure [115]. Providing comfort in clothing for a moving body is a difficult challenge. The number of interconnections between body sizes and shapes, physiological variances, material properties, design choices, environmental challenges and activities is exponential. Clothing has a tremendous impact on worker's comfort and performance in the workplace. In accordance with industrial protection standards, cut-protective workwear is often selected based on functionality and safety [116]. The influence of cut-protective workwear on performance is dependent on the type of task, the required metabolism rate, the surrounding environment and the protective workwear attributes [117]. The ergonomic specifications and characteristics based on the level of relevance for factory workers are as follows: (1) correct fit or size; (2) decrease in heat, as well as improved air circulation through pattern, design and material selection; (3) weight reduction and removal of work-related impediments; and (4) mobility [118]. Many protective workwear standards have been adopted in recent years, and have helped improve the quality of cut-protective workwear and increase worker safety [119]. Cut-protective workwear has significant negative effects, while ergonomic issues often arise with increasing security needs. The main problem is often the additional weight on the body. Furthermore, decreased mobility caused by garment stiffness restricts flexible motion and could increase the risk of falling or becoming entangled in the apparatus. For this reason, cut-protective clothing may worsen rather than improve safety, especially over time. As a result, the user may choose not to wear the necessary protection. Consequently, the shape and material layers of cut-protective workwear need to be carefully chosen to balance protection and comfort, with an emphasis on selecting the lightest and most breathable system that provides enough thermal resistance.

7 Future directions

The incorporation of nanotechnology in textiles is leading to the creation of fabrics that offer improved cut resistance, durability and comfort. Nanoparticles can provide features such as water repellence, stain resistance, UV protection and antimicrobial properties, all while maintaining the fabric's flexibility and breathability. For instance, graphene and other 2D materials are being studied for their outstanding mechanical and electrical properties, opening new opportunities for lightweight and strong protective clothing [120]. Manufacturing advancements now facilitate highly customizable cut-resistant clothing, allowing users to choose materials, garment types and reinforcement options that suit their specific requirements for comfort and protection. This trend towards personalization is supported by digital technologies such as 3D printing, robotics and advanced textile processing, which also facilitate quick prototyping and scalable production. Customization also extends to fit and ergonomics, focusing on creating garments that cater to various body shapes and movements to enhance comfort and reduce fatigue during extended wear [121]. The future of cut-protection clothing involves integrating wearable sensors that can monitor the wearer's health and the garment's condition seamlessly. Embedded sensors can monitor vital signs, detect exposure to hazards and notify users of any breaches in protection. Graphene-based e-textiles are being developed for their flexibility, washability and potential to accommodate complex sensor arrays [122].

8 Conclusion

Cut-protective clothing requires specialized design and engineering approaches distinct from conventional fashion apparel, due to the need for high-performance materials and advanced construction techniques that ensure both safety and comfort. Current innovations, including the use of nanotechnology,

smart textiles and adaptive materials, are making garments lighter, more flexible and more durable, and thus directly addressing user needs for comfort and efficiency in demanding environments. The lack of universal standards and the complexity of regulatory compliance remain significant challenges, especially as new technologies and materials are introduced. Ensuring that protective clothing meets both local and international safety standards is critical for effective protection and market acceptance. Garments must be tailored to specific occupational hazards, environmental conditions and user demographics, including considerations for gender and body type, to maximize both protection and usability. Multidisciplinary collaboration among engineers, designers, physiologists, ergonomists and end-users is vital for overcoming challenges in material selection, garment construction and performance evaluation. This review highlights the importance of integrating advanced materials science, user-focused design and regulatory awareness in the development of next-generation cut-protective clothing. Advances in materials, design and technology are transforming cut-protective clothing. However, realizing the full potential of these innovations requires a focused effort on standardization, user-specific solutions and cross-disciplinary collaboration. These steps will ensure that protective garments not only meet the highest safety standards but also deliver comfort, sustainability and practical value across diverse industries.

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Customization of Brassiere Underwire Design: Leveraging 3D Printing for Enhanced Pressure Distribution

Individualna prilagoditev oblike oporne žice v nedrčku: uporaba 3-D tiska za izboljšano porazdelitev pritiska

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Abstract

Conventional brassiere underwires often cause discomfort due to localized pressure concentrations, leading to wearer discomfort and potential long-term health concerns. This study investigates the application of 3D printing technology for designing and fabricating customized brassiere underwires aimed at improving pressure distribution and structural comfort. A 3D body scan of the under-bust profile was utilized to develop a personalized underwire model, which was fabricated using fused deposition modelling (FDM) with acrylonitrile butadiene styrene (ABS) material. To evaluate performance, pressure exertion tests were conducted using force-sensitive sensors positioned at three anatomical points, Point A (base region), Point B (medial region, near the sternum) and Point C (lateral region, near the underarm), under both static and dynamic conditions. The 3D-printed underwire demonstrated significant reductions in localized pressure compared to the conventional stainless-steel underwire, achieving decreases of 36.36% at Point A, 38.10% at Point B and 35.00% at Point C under static conditions, and 24.00%, 21.74% and 22.22%, respectively, under dynamic conditions. Complementary finite element analysis (FEA) was performed to simulate structural deflection under breast loads ranging from 0.5 kg to 0.8 kg. The results indicated that the maximum deflection increased from 1.48 mm to 2.37 mm, while average deflection rose from 0.80 mm to 1.28 mm, demonstrating a linear elastic behaviour consistent with the mechanical properties of ABS (Young's modulus \approx 2.0 GPa) compared to stainless steel (\approx 200 GPa). The deformation contour confirmed effective load distribution with minimal deflection in the constrained regions, validating structural stability. Overall, the findings establish that 3D-printed ABS underwires provide improved comfort, controlled flexibility and reliable mechanical performance, making them a viable alternative to traditional metallic underwires. This research highlights the potential of additive manufacturing in the intimate apparel industry, enabling mass customization, enhanced anatomical conformity and improved wearer satisfaction beyond conventional mass-produced designs.

Keywords: 3D printing, brassiere, underwire, comfort, pressure distribution, FEA



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Izvleček

Konvencionalne oporne žice (opornice) v nedrčkah pogosto povzročajo nelagodje zaradi lokaliziranih koncentracij pritiska, kar vodi v nelagodje pri nošenju in morebitne dolgoročne zdravstvene težave uporabnice. Ta raziskava se osredinja na uporabo tehnologije 3-D tiska za oblikovanje in izdelavo prilagojenih opornic za nedrčke, katerih namen je izboljšati porazdelitev pritiska in strukturno udobje. Na podlagi 3-D skeniranega profila podprsa je bil z uporabo modeliranja taljenega nanosa (FDM) z materialom akrilonitril butadien stiren (ABS) izdelan posamezni osebni prilagojen model opornice. Učinkovitost kosti je bila ocenjena iz rezultatov testiranja pritiska s pomočjo senzorjev za silo, nameščenih na treh anatomskih točkah: točki A (osnovno območje), točki B (medialno območje, blizu prsnice) in točki C (lateralno območje, blizu pazduhe), in sicer v statičnih in dinamičnih razmerah. 3-D natisnjena opornica je pokazala znatno zmanjšanje lokaliziranega pritiska v primerjavi s konvencionalno opornico iz nerjavnega jekla, in sicer zmanjšanje za 36,36 % v točki A, 38,10 % v točki B in 35,00 % v točki C v statičnih razmerah ter 24,00 %, 21,74 % oziroma 22,22 % v dinamičnih razmerah. Za simulacijo strukturnega odklona pri obremenitvah prsi od 0,5 kg do 0,8 kg je bila uporabljena metoda končnih elementov (MKE). Pokazalo se je, da se je največji odklon povečal z 1,48 mm na 2,37 mm, povprečni odklon pa z 0,80 mm na 1,28 mm, kar kaže na linearno elastično obnašanje, ki je skladno z mehanskimi lastnostmi ABS (Youngov modul $\approx 2,0$ GPa) v primerjavi z nerjavnim jeklom (≈ 200 GPa). Kontura deformacij je potrdila učinkovito porazdelitev obremenitve z minimalnim odklonom v omejenih območjih, kar je potrdilo strukturno stabilnost. Splošna ugotovitev je, da 3-D tiskane opornice ABS zagotavljajo izboljšano udobje, nadzorovano upogibljivost in zanesljivo mehansko delovanje, kar pomeni, da so primerna zamenjava za tradicionalne kovinske opornice. Ta raziskava poudarja primernost aditivne izdelave v proizvodnji spodnjega perila, ki omogoča množično izdelavo po meri, izboljšano anatomsko skladnost in zadovoljstvo uporabnic, ki presega običajne konfekcijsko proizvedene modele.

Ključne besede: 3-D tiskanje, modrček z oporo, udobje, porazdelitev pritiska, metoda končnih elementov (MKE)

1 Introduction

The evolving lifestyle and diverse needs of modern women have profoundly influenced the design of clothing, particularly in the domain of lingerie. With the increasing physical and mental demands of daily life, comfort has become a fundamental requirement for maintaining productivity, well-being and confidence. Recognizing that each woman has unique body characteristics and personal preferences, lingerie designers and manufacturers are increasingly adopting personalization and customization as key strategies in garment development. Recent research demonstrates that the use of inverse design methods can successfully customize bra cups, thereby significantly improving fit and user satisfaction. This evolution emphasizes the necessity of integrating en-

gineering principles into garment design to achieve optimal comfort, support and aesthetic appeal [1].

Anatomically, the female breast is a complex structure composed of mammary glands, adipose tissues, connective tissues and blood vessels, enclosed by a sensitive skin layer that contributes to femininity and physical appearance. Unlike other body parts, the breasts lack direct muscular and skeletal support and instead rely on Cooper's ligaments and superficial fascia for lift and positioning. These ligaments, however, are highly susceptible to mechanical stress during physical movement, which can lead to breast ptosis (sagging). Consequently, the design of brassieres that provide both comfort and adequate support has become increasingly

important. Over the years, brassieres have evolved from simple functional garments into highly engineered support systems that integrate biomechanics, material science and ergonomic design. A well-fitted brassiere is crucial for minimizing breast discomfort, preventing musculoskeletal strain and enhancing posture [2].

Studies have shown that ill-fitting brassieres can cause shoulder pain, back pain and discomfort, particularly among women with larger bust sizes [3]. Among various bra types, underwire brassieres play a vital role in shaping and supporting the breasts. The underwire, typically a rigid U-shaped component made of metal or plastic, is sewn into a channel beneath the cups, providing lift and maintaining contour. To prevent the wire from piercing the fabric, both ends are covered with plastic tips or cushion caps [4]. Metallic materials, primarily steel and nickel-titanium alloys, dominate underwire production due to their superior rigidity and durability [5]. In contrast, plastic underwires, usually made from polypropylene or PVC, account for a small market share because of their lower stiffness and susceptibility to permanent deformation under load. However, ABS offers enhanced tensile strength, thermal resistance, and dimensional stability compared to other thermoplastics, making it a promising candidate for underwire applications requiring structural performance.

Research has confirmed that underwired brassieres effectively reduce vertical breast displacement and improve breast positioning, thereby enhancing support [6]. Continued advancements in underwire materials and geometry have also improved comfort by minimizing localized pressure points and improving ergonomic performance [7]. Nevertheless, many women report discomfort from underwires due to excessive stiffness and pressure concentration along the chest wall. Poorly fitted underwires can lead to skin irritation, inflammation and pressure-related pain [8]. Common design flaws include improper curvature and arc length, which may cause the wire to poke through the fabric or rub against the skin

[9]. Prolonged pressure from underwires has been associated with mastitis and myalgia, although no scientific evidence supports a causal link to breast cancer [10]. Additional discomfort often arises from shoulder strap pressure, compounding wearer dissatisfaction [11].

In this context, 3D printing (additive manufacturing) presents a promising solution for creating personalized lingerie components. This technology enables the fabrication of complex three-dimensional objects layer by layer from digital models, facilitating precise customization and geometric flexibility. The fashion industry has increasingly adopted 3D printing for producing jewellery, footwear, accessories and garments [12–14]. Techniques such as FDM facilitate the production of textile-like structures suitable for wearable applications [15]. The integration of 3D printing in lingerie design enables the creation of customized underwires tailored to individual body contours, thereby improving fit, comfort and aesthetic harmony [16]. Prior studies using 3D scanning to capture breast root contours have demonstrated the potential for developing personalized underwires that enhance anatomical conformity and wearer comfort [17]. Moreover, several brands and researchers are advancing toward mass personalization in intimate apparel through 3D body scanning, parametric modelling and data-driven fitting algorithms [18].

The aim of this study was to design and fabricate a customized brassiere underwire using 3D printing technology to achieve enhanced pressure distribution and user comfort. A 3D body scanning technique was employed to obtain an accurate under-bust profile, which was then processed into a digital model for additive manufacturing. The resulting ABS underwire was experimentally tested to measure pressure exertion at critical points, while FEA was conducted to evaluate its structural response under different load conditions. Comparative assessments with conventional stainless-steel underwires were performed to examine comfort and structural integrity. The outcomes provide valuable

insights into integrating digital design and additive manufacturing in lingerie development for improved comfort, performance and personalization.

2 Materials and methods

2.1 Acquisition of 3D body scan and underwire design

The design and evaluation of the customized 3D-printed underwire began with the acquisition of the under-bust profile using a high-precision 3D body scanning technique. A participant with a brassiere size of 38C was selected for this study to represent an average larger-cup size, which typically experiences higher pressure concentration under the bust. The scanning was performed using a Shining 3D EinScan Pro 2X Plus, a structured-light 3D scanner known for its high accuracy and ability to capture fine surface details. The scanner was operated in handheld rapid mode, facilitating complete acquisition of the under-bust curvature without causing any discomfort to the subject.

The captured three-dimensional point cloud data was processed using Geomagic Design X software to reconstruct the anatomical under-bust curve and remove scanning noise or misalignment. The processed geometry provided an accurate digital representation of the breast root contour, which served as the basis for customized underwire design. Using computer-aided design (CAD) tools, the underwire was modelled with optimized curvature and width ratios to achieve balanced support and minimal localized pressure. Several iterative CAD simulations were performed to refine the geometry, ensuring a comfortable anatomical fit and effective pressure dispersion.

The final design consisted of two main structural components: a cup portion and a flap portion. The cup portion, designed with a thickness of 1.5 mm and width of 2.5 cm, followed the natural curvature of the under-bust, tapering gradually toward the inner and outer breast regions. This design ensured a close fit along the chest wall while maintaining

sufficient flexibility. The flap portion, measuring 4 mm in thickness and 7 mm in width, was connected to the lower edge of the cup. Its function was to distribute the applied load over a broader area, thereby reducing localized high-pressure points at the skin interface.

The completed 3D model was digitally aligned with the scanned under-bust surface to verify conformity and dimensional accuracy before proceeding to fabrication. The final assembly, illustrated in Figure 1, shows the precise fitting of the designed underwire onto the breast root curvature, confirming ergonomic and structural compatibility.

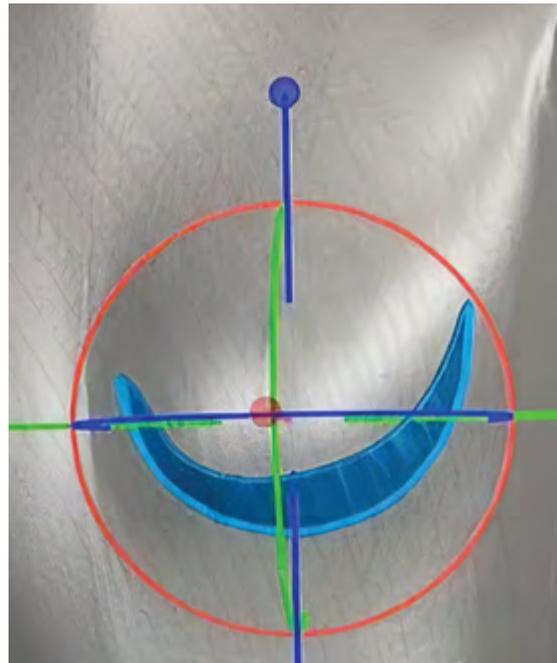


Figure 1: 3D model of underwire fitted along the breast root contour

2.2 3D Printing of underwire

The finalized 3D model of the customized underwire was fabricated using FDM, one of the most widely adopted additive manufacturing techniques for polymer-based components. This process was chosen for its cost-effectiveness, geometric versatility and ability to produce lightweight yet durable parts suitable for wearable applications. The printing was carried out using an Ultimaker S5 3D printer, which

offers a high level of dimensional accuracy and surface quality appropriate for fine, curved geometries such as underwire structures.

ABS filament was selected as the printing material due to its superior mechanical properties, including high tensile strength, toughness and thermal stability. These characteristics make ABS ideal for producing components that require flexibility under cyclic loading without permanent deformation. The filament diameter used was 1.75 mm, while the printer's nozzle diameter was set to 0.4 mm. To achieve optimal strength and surface smoothness, the printing parameters were standardized as follows: printing temperature of 240°C, bed temperature of 100°C, printing speed of 50 mm/s and layer height of 0.1 mm. The infill density was maintained at 100% (solid) to ensure maximum structural integrity and consistent load-bearing performance.

The underwire was printed in a horizontal orientation to enhance dimensional stability and reduce internal stress accumulation during cooling. After printing, the component was allowed to cool gradually on the print bed to prevent warping or delamination. Post-processing involved support structure removal and light surface finishing using fine-grit sandpaper to achieve a smooth and skin-safe surface texture.



Figure 2. 3D printed underwire component

The printed underwire was subsequently evaluated for dimensional accuracy using digital callipers and was compared to the CAD model to confirm tolerance levels within ± 0.2 mm. As illustrated in Figure 2, the 3D-printed underwire demonstrated high structural fidelity to the digital design. The fabricated underwire was then integrated into a specially prepared brassiere casing for experimental evaluation, as shown in Figure 3.



Figure 3: Attachment of 3D printed underwire in a casing with the cup

2.3 Pressure exertion test

Bra comfort is fundamentally influenced by the distribution of pressure exerted during wear, which can be assessed using direct or indirect evaluation methods [19]. Studies have shown that integrating cushioning elements between the bra strap and the body significantly enhances pressure distribution and overall comfort [20]. To evaluate the pressure exerted by the underwire on breast tissue, a pressure exertion test was conducted using force-sensitive resistor (FSR) sensors.

In this study, pressure mapping was performed following a customized test protocol designed to capture the pressure exerted at key anatomical regions beneath the breast. Based on ergonomic relevance and previous research [21], three critical sensor locations Point A (base region), Point B (medial region, near the sternum) and Point C (lateral region, near the underarm) were selected to measure both vertical and lateral support responses. These sensor locations were identified as areas prone to concentrated pressure during wear [22].

FSR sensors were affixed to the inner surface of the brassiere, directly below the underwire, ensuring precise alignment with the designated anatomical points. Each participant wore both types of brassieres: one fitted with a 3D-printed ABS underwire and another with a conventional stainless-steel underwire. The tests were conducted under controlled laboratory conditions to ensure consistency in posture, fit and motion. Pressure readings were collected under two states: static (stationary posture) and dynamic, which simulated natural body movements such as arm lifting, torso twisting and short walking cycles.

The sensors were calibrated prior to testing to ensure high measurement accuracy and repeatability. Pressure values were continuously recorded and expressed in N/cm^2 , computed from the measured force and sensor's active area. The data collected from Points A, B and C provided a comprehensive representation of pressure distribution under both static and dynamic conditions, enabling a direct comparison between the two underwire types.

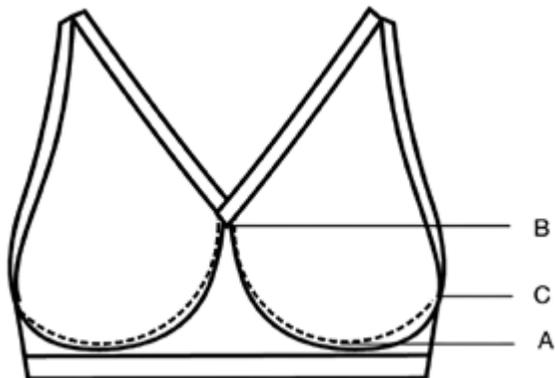


Figure 4: Sensor points A, B and C on the breasts

The spatial locations of the sensors and their corresponding measurement points are illustrated in Figure 4, which provides a schematic representation of the under-bust region showing the placement of Points A, B and C. This configuration ensured consistent data acquisition from regions most relevant to underwire-induced pressure during wear.

2.4 Finite element analysis (FEA)

Finite element analysis (FEA) was conducted using the ANSYS static structural module to evaluate the deflection behaviour of the 3D-printed underwire under varying loading conditions. A fine mesh was generated using tetrahedral solid elements to ensure high accuracy in predicting stress and deformation. The underwire model was constrained at both ends to replicate its fixed attachment points within the brassiere frame.

A pressure boundary condition was applied along the curved surface of the underwire, corresponding to estimated breast loads in the range of 0.5–0.8 kg. This load interval represents the average breast weight for women with larger cup sizes, typically varying from approximately 500 grams to over 1 kilogram, and includes the expected range for a 38C cup size, as reported in previous anatomical studies [22]. The simulation was performed under static loading conditions using the standard ANSYS solver to ensure stable and realistic results.

Material properties corresponding to ABS were assigned based on standard reference values, including its Young's modulus and Poisson's ratio, to accurately model the material's mechanical behaviour. The deflection of the underwire was then computed under the distributed load to quantify deformation characteristics representative of real-world wearing conditions.

3 Results and discussion

3.1 Pressure exertion test

A pressure exertion test was conducted to assess the distribution of pressure applied by the underwires on the wearer's body, as this parameter directly influences comfort and ergonomic performance. Excessive localized pressure can lead to discomfort, irritation and long-term skin issues, making it essential to evaluate how different materials and structural modifications affect pressure distribution. The results of the pressure exertion test, summarized in Table 1, demonstrate that the 3D-printed under-

wire consistently exhibited lower pressure values under both static and dynamic conditions across all measurement points A (base region), B (medial region) and C (lateral region) compared to the conventional stainless-steel underwire, as depicted

in Figure 5. Pressure values increased slightly during dynamic motion due to natural variations in force distribution. However, the 3D-printed underwire demonstrated superior adaptability and stability compared to the rigid stainless-steel design.

Table 1: Pressure testing results

Point	Pressure (N/cm ²)			
	Static test		Dynamic test	
	3D-printed underwire	Stainless steel underwire	3D-printed underwire	Stainless steel underwire
A	0.28	0.44	0.38	0.50
B	0.26	0.42	0.36	0.46
C	0.26	0.40	0.35	0.45



Figure 5: Stainless steel underwire

The most significant reduction in pressure was observed at Point B (medial region), indicating improved comfort and better load redistribution in this area. This supports the effectiveness of the customized 3D-printed design in distributing force more evenly across the under-bust region. These findings are in line with prior studies emphasizing that softer and geometrically adaptive components can enhance wear comfort by minimizing high-pressure zones beneath the bust [19, 20].

A comparative analysis further revealed that the 3D-printed underwire achieved substantial pressure reductions relative to the conventional model. Under static conditions, the reductions were 36.36% at Point A, 38.10% at Point B and 35.00% at Point C. Under dynamic conditions, pressure reductions were 24.00% at Point A, 21.74% at Point B and 22.22% at Point C. These improvements are attributed to the enhanced flexibility and form-fitting nature of the

ABS underwire, which allows it to conform more effectively to the natural body contours compared to its rigid stainless-steel counterpart.

No abrupt pressure spikes were detected in the 3D-printed underwire, indicating smoother and more uniform pressure transitions. A minor increase observed at Point B during dynamic movement suggests that localized geometric optimization in future design iterations could further improve comfort. Overall, the lower pressure values recorded for the 3D-printed underwire confirm its potential to reduce discomfort and irritation, particularly during prolonged wear. Furthermore, the dynamic test results validate its superior performance during motion, reducing transient pressure peaks and enhancing overall comfort. These outcomes demonstrate the feasibility of utilizing 3D printing to develop ergonomically optimized underwire designs that achieve improved pressure distribution and wearer satisfaction.

3.2 Finite element analysis (FEA)

FEA was conducted to examine the deformation characteristics of the 3D-printed ABS underwire under varying breast loads and to compare its performance with a conventional stainless-steel underwire of identical geometry. The results are presented in Table 2, which presents the maximum deflection values obtained for each load condition.

Table 2: Comparative FEA deflection results

Load (kg)	Maximum deflection (mm)	
	ABS underwire	Stainless steel underwire
0.5	1.48	0.015
0.6	1.78	0.018
0.7	2.08	0.021
0.8	2.38	0.024

A clear contrast was observed between the deformation behaviours of the two materials. The stainless-steel underwire, owing to its high stiffness (Young's modulus ≈ 200 GPa), exhibited minimal deflection across all load cases, with a maximum of 0.024 mm at 0.8 kg. Conversely, the ABS underwire, with a significantly lower Young's modulus of approximately 2.0 GPa, demonstrated greater but controlled flexibility, with deflections increasing from 1.48 mm at 0.5 kg to 2.38 mm at 0.8 kg. This gradual rise in deformation with increasing load indicates a linear elastic response, consistent with the mechanical properties of both materials.

The controlled deflection of the ABS underwire plays a key role in enhancing comfort by facilitating slight structural adaptability under load. Unlike the rigid stainless-steel wire, which confines the breast in a fixed position, the ABS underwire behaves as a compliant spring, absorbing and redistributing the applied load through elastic deformation. This flexibility helps minimize localized stress concentrations, particularly at the medial and lateral regions identified during the pressure exertion tests, thereby reducing wearer discomfort.

The deflection results of the ABS underwire obtained from the finite element analysis (FEA) are illustrated in Figure 6, which presents a line chart showing the deflection variation along the underwire's bottom edge curve for breast weights ranging from 0.5 kg to 0.8 kg. The deflection values were analysed in terms of minimum, maximum and average magnitudes for each load case. At a 0.5 kg load, the minimum deflection recorded was 2.53×10^{-17} mm, the maximum value was 1.4848 mm and the average value was

0.8031 mm. For 0.6 kg, these values increased to 3.04×10^{-17} mm, 1.7818 mm and 0.9637 mm, respectively. Similarly, at 0.7 kg, the minimum deflection reached 3.54×10^{-17} mm, the maximum was 2.0788 mm and the average was 1.1243 mm. Under the highest tested load of 0.8 kg, the minimum, maximum and average deflections were 4.05×10^{-17} mm, 2.3758 mm, and 1.2850 mm, respectively.

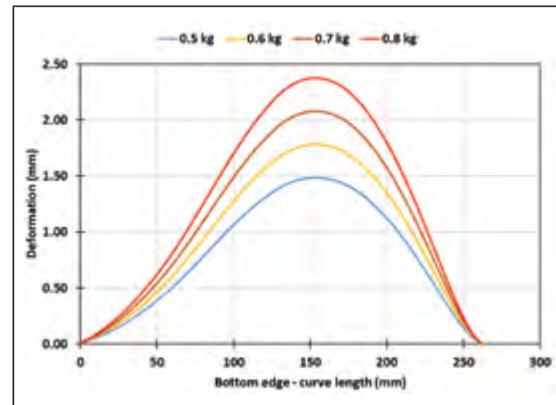


Figure 6: Finite element analysis line chart showing deflection of the ABS underwire for breast weights ranging from 0.5 kg to 0.8 kg

A comparison across the four load cases shows a nearly linear increase in deflection with increasing load. The maximum deflection rose by approximately 23.2% between 0.5 kg and 0.6 kg, by 16.7% between 0.6 kg and 0.7 kg, and by 14.3% between 0.7 kg and 0.8 kg, reflecting a gradually decreasing rate of increase. The consistent proportionality between load and deflection demonstrates that the ABS underwire behaves elastically within the tested range and maintains structural integrity under incremental loading conditions.

The FEA deflection contour of the ABS underwire, illustrated in Figure 7, shows that the maximum deformation occurred near the central region of the underwire where the downward breast load is concentrated while the end regions, constrained within the brassiere frame, exhibited minimal deflection. This deformation pattern indicates that the underwire effectively distributes the applied load along its

curvature, minimizing local stress concentrations and preventing structural instability.

Overall, the analysis confirms that the 3D-printed ABS underwire exhibits controlled deflection behaviour under loads ranging from 0.5 kg to 0.8 kg, maintaining sufficient stiffness to support the breast while providing the flexibility needed to enhance comfort. The relatively low maximum deflection

values demonstrate that the structure can withstand typical breast weights without excessive bending, while the distributed deformation pattern ensures uniform support. These findings validate the mechanical feasibility of 3D-printed ABS underwires as a comfortable, adaptive and structurally reliable alternative to traditional metallic underwires in brassiere design.

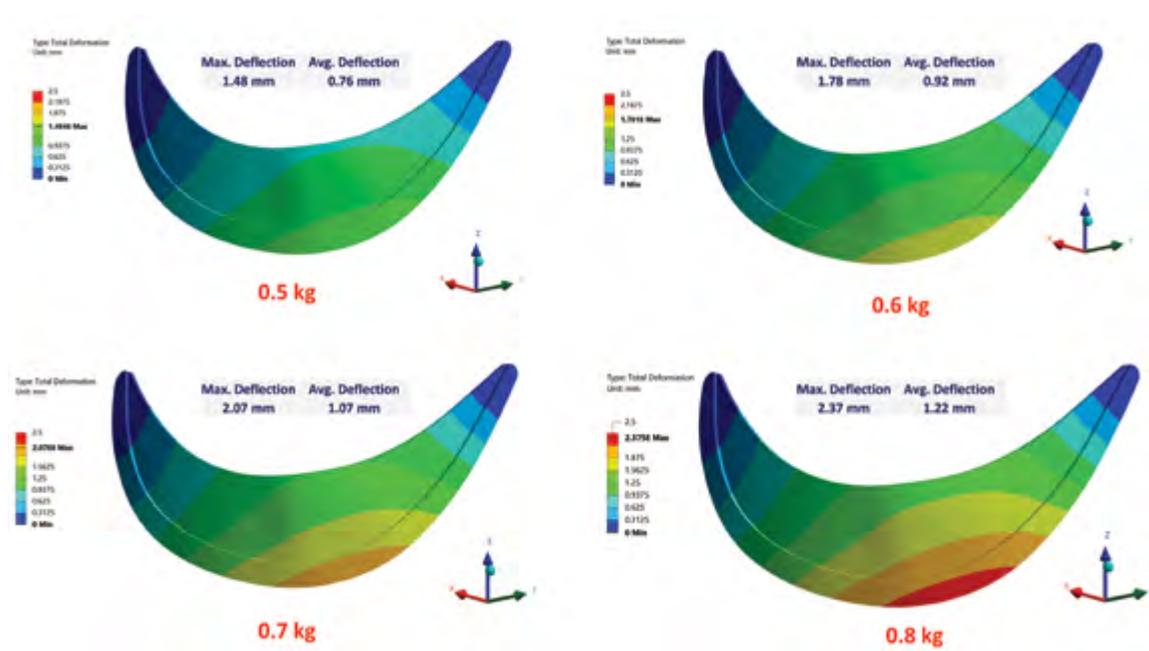


Figure 7: ABS underwire deflection distribution contour visualization for breast weights of 0.5 kg to 0.8 kg

4 Conclusion

This study successfully demonstrated the potential of 3D printing technology in the customization of brassiere underwires to enhance wearer comfort and optimize pressure distribution. The primary objective to design a personalized underwire tailored to an individual's under-bust profile was achieved through 3D body scanning and digital modelling techniques. The fabricated underwire, produced using FDM with ABS material, offered a structurally stable and ergonomically comfortable alternative to conventional stainless-steel underwires.

The pressure exertion test results confirmed that

the 3D-printed underwire effectively reduced localized pressure at critical contact points under both static and dynamic conditions. Compared to traditional stainless-steel underwires, the 3D-printed design achieved substantial reductions in localized pressure at all three measured points, resulting in a more uniform force distribution. This improvement directly translated to enhanced wearer comfort and mitigated discomfort commonly associated with rigid metallic underwires.

The FEA results further validated the mechanical reliability of the 3D-printed underwire under varying breast load conditions. The deformation contour indicated that the highest deflection occurred at the

central region, where breast load concentration is greatest, while maintaining structural stability across the overall geometry. This pattern confirmed the ability of the customized design to distribute applied loads efficiently without excessive deformation, aligning with the pressure test findings.

Overall, this research highlights the feasibility and effectiveness of 3D-printed underwires as a viable alternative to conventional metallic designs. The ability to customize underwires based on individual anatomical profiles introduces a personalized approach to lingerie design, improving both comfort and functional support. Future studies may further refine this concept by exploring alternative materials, composite filament blends and optimized structural geometries to enhance flexibility and long-term durability.

Additionally, future studies should include comparative assessments between 3D-printed ABS underwires and conventional moulded plastic underwires, thereby establishing a broader understanding of the advantages and trade-offs associated with different fabrication techniques. Expanding the study to encompass multiple participants across a wider range of cup and band sizes will provide deeper insights into variations in fit, comfort and pressure distribution.

The findings from this research provide valuable guidance for lingerie designers and manufacturers, emphasizing the potential of digital design integration and additive manufacturing in intimate apparel development. The demonstrated approach facilitates mass customization, improved anatomical conformity and potentially more sustainable production models. Ultimately, the adoption of such advanced design methodologies could lead to underwires that are tailored to individual body scans, offering improved comfort, durability and fit across diverse body types, paving the way for a new generation of custom-fitted, high-comfort brassiere solutions.

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Experience of Students at Faculty of Natural Sciences and Engineering, University of Ljubljana in Using Online Classrooms

Izkušnja študentov Naravoslovnotehniške fakultete Univerze v Ljubljani pri uporabi spletnih učilnic

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Abstract

The aim of the study was to determine the progress in the use of online classrooms, gather opinions on their functional use on computers or mobile devices, on user interface and its elements, work within online classrooms, and on the advantages and disadvantages of conducting examinations in online classrooms. The research involved students from various study programmes, including students of textile and clothing study programmes, and focused on analysing the use of Moodle online classrooms through the system's built-in tools and student surveys. The results indicate that the number of users of online classrooms is increasing. Students access online classrooms via computers and, increasingly, via mobile devices. The overall appearance of online classrooms was assessed as appropriate on both computers and mobile devices, with some comments suggesting improvements in the personalisation of the dashboard and better visual organisation. Students were satisfied with the arrangement and accessibility of control elements on both types of devices and praised the typography used, while expressing less satisfaction with some of the icons representing certain functions. Remarks were also made regarding the unclear labelling of some functions or commands. The information displayed on both devices was considered visible, although its retrieval on mobile devices was perceived as time-consuming. Students reported becoming familiar with the online classroom quickly and appreciated their practicality. They were satisfied with the organisation of content by chapters. A smaller number of students uses the online classroom for exchanging opinions or group work, while they still prefer email communication for interaction with lecturers. Students praised the simplicity of submitting assignments via the online environment (esp. group assignments) and the opportunity to receive feedback from assessors. They did not encounter major difficulties when taking exams within the online classroom. They found the technical implementation straightforward, the information provided in the examination (quiz) environment useful, and the appearance of the exam interface pleasant. The findings of the study indicate the need for improvements primarily in the area of the user interface and in encouraging greater use of tools that enable



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direct communication among participants within online classrooms. It is also recommended that the faculty provide targeted professional training for academic and technical staff in the advanced functionalities of Moodle, promote the inclusion of interactive and collaborative learning activities, establish coherent pedagogical guidelines for online course design, systematically collect and apply user feedback, and encourage the use of digitally supported forms of teaching.

Keywords: engineering, natural sciences, online classroom, Moodle, digitisation, user experience

Izvleček

Cilj raziskave je bil ugotoviti napredek pri uporabi spletnih učilnic, zbrati mnenja o funkcionalni uporabi spletnih učilnic na računalnikih ali mobilnih napravah, uporabniškem vmesniku in njegovih elementih, delu v spletnih učilnicah ter o prednostih in slabostih izvajanja izpitov v spletnih učilnicah. V raziskavo so bili vključeni študenti različnih študijskih programov (tudi študenti tekstilstva), osredotočala pa se je na analizo uporabe spletnih učilnic Moodle z uporabo vgrajenih orodij sistema ter anket med študenti. Rezultati kažejo, da število uporabnikov spletnih učilnic narašča. Do učilnic dostopajo s pomočjo računalnikov in v vedno večjem številu tudi s pomočjo mobilnih naprav. Splošni izgled učilnic je tako na računalnikih kot mobilnih napravah ocenjen kot ustrezen z nekaterimi opombami glede personalizacije nadzorne plošče in boljše preglednosti. Študenti so bili zadovoljni z razporeditvijo in dostopnostjo kontrolnikov na obeh napravah, pohvalili so uporabljeno tipografijo, manj zadovoljni pa so bili z uporabljenimi ikonami za nekatere funkcije. Podane so bile tudi opombe na nerazumljivo poimenovanje nekaterih funkcij/ukazov. Informacije na zaslonih obeh naprav so bile ocenjene kot vidne, njihovo iskanje na mobilnih napravah pa zamudno. Študenti so se v spletnih učilnicah hitro znašli, pohvalili pa so tudi njihovo praktičnost. Zadovoljni so bili z razporeditvijo vsebin po poglavjih. Manjše število študentov spletno učilnico uporablja za izmenjavo mnenj ali skupinsko delo, za interakcijo z učiteljem pa še vedno raje uporabljajo e-pošto. Pohvalili so enostavnost oddajanja nalog v spletno učilnico (predvsem skupinskih nalog) ter možnost povratne informacije ocenjevalcev. Večjih težav pri opravljanju izpitov v spletni učilnici niso zaznali; tehnična izvedba se jim je zdela preprosta, informacije v izpitnem okolju (kvizu) uporabne, izgled izpita pa prijeten. Ugotovitve raziskave nakazujejo nujnost izboljšav predvsem na področju uporabniškega vmesnika in večjega spodbujanja uporabe tistih orodij, ki omogočajo neposredno komunikacijo med udeleženci v spletnih učilnicah. Priporočljivo je tudi, da fakulteta izvaja ciljno usmerjeno strokovno usposabljanje za visokošolske in tehnične sodelavce na področju naprednih funkcionalnosti sistema Moodle, spodbuja vključevanje interaktivnih in sodelovalnih učnih dejavnosti, vzpostavi usklajene pedagoške smernice za spletno načrtovanje predmetov, sistematično zbira in uporablja povratne informacije uporabnikov ter spodbuja uporabo digitalno podprtih oblik poučevanja.

Ključne besede: inženirstvo, naravoslovje, spletna učilnica, Moodle, digitalizacija, uporabniška izkušnja

1 Introduction

The digital transformation of higher education has reshaped the ways in which knowledge is created, communicated and evaluated, presenting universities around the world with both challenges and opportunities. In the European and broader international context, higher education institutions have adopted

digital education strategies to improve the quality of teaching, expand access to knowledge and learning, and promote sustainable innovation in pedagogical practices [1, 2]. Digital transformation is not just a technological shift, but a comprehensive pedagogical and institutional transformation that redefines the

processes of teaching, learning and assessment. Research emphasises that digital technologies enable greater flexibility, interactivity and accessibility of the learning process; however, their effective integration depends on the pedagogical and digital competences of educators and adequate institutional support to promote digital innovation [3].

1.1 Theoretical and conceptual foundations of digital pedagogy

The development of digital education has gradually shifted focus from the functional introduction of technologies to a more in-depth understanding of learners' experiences, promoting inclusion and sustainable practices. Theoretical approaches such as constructivism and self-regulated learning [4], and models such as the Technology Acceptance Model (TAM) [5, 6] offer guidance for understanding how individuals adopt and use educational technology. The TAM model emphasises perceived usefulness and ease of use as key factors influencing users' behavioural intentions – a perspective that has been repeatedly confirmed in the higher education context, including in the studies on the use of the Moodle online classroom system [7].

Approaches based on constructivist and social constructivist pedagogy emphasise that the integration of educational technologies should promote autonomy, collaboration and reflection among learners [4]. These theories place the learner in the centre of the learning process as an active co-creator of knowledge, which is built through interaction with peers, learning content and digital learning environments. Researchers [8] expand on this argument by emphasising that the effective use of digital learning management systems (LMS) requires not only technical competences but also a comprehensive understanding of didactic and technological pedagogical content knowledge (TPACK model). Their findings are based on an extensive study conducted among 640 higher education teachers, which shows that LMS platforms are often used primarily as repositories for materials rather than comprehensive support environments

for collaborative learning, implementing formative knowledge assessment and providing feedback.

Furthermore, the digital transformation in education must be aligned with the development of digital competences among both students and educators [9]. The European Commission's Action Plan for Digital Education emphasises this alignment and calls for the improvement of digital literacy, equal access and lifelong learning through inclusive educational ecosystems [1, 2]. Studies in recent years have shown that educators need dedicated time, professional support and opportunities for collaborative learning to effectively integrate educational technologies into their teaching [3].

1.2 User experience in digital learning environments

A growing body of literature explores the user experience (UX) of teachers and learners in digital learning contexts. User experience encompasses usability, engagement, satisfaction, interest and perceived learning effectiveness in digital learning environments. Research at European universities has shown that the quality of the digital user experience depends on institutional support, intuitive interface design and the alignment of tool use with pedagogical goals [10]. The rapid transition to online and blended learning during the COVID-19 pandemic has further highlighted differences in digital readiness and emphasised the need for robust, user-friendly learning environments [11].

Moodle, as one of the most widely used online learning environments in the world, has been the focus of studies examining user experience and learning outcomes. Researchers [12] showed that patterns of student engagement captured by Moodle analytics can predict academic performance, highlighting the potential of learning analytics for personalised feedback and early intervention. Similarly, studies on personalisation and adaptive learning paths in Moodle environments [13] reveal the importance of designing flexible, student-centred experiences that respond to the diverse learners' needs.

Recent empirical studies have expanded the analysis of online learning contexts beyond technological possibilities to include social and psychological dimensions. Lavidas et al. [14] examined how social desirability influences students' self-evaluation in different learning environments and showed that contextual factors such as learning mode (lectures versus laboratory exercises) shape students' perceptions and engagement patterns. In a related study, Lavidas, Petropoulou et al. [15] identified factors that influence the level of teacher response in online environments, highlighting authority, incentives and environment structure as determinants of digital collaboration and engagement. These findings are important for explaining user behaviour in online classrooms.

1.3 Moodle in context of digital education

In the broader context of educational technologies, Moodle occupies a special place as an open-source learning management system based on constructivist pedagogy. Its modular architecture allows educators to design learning environments that combine tools for communication, collaboration and assessment [4]. Moodle's openness and flexibility have enabled its widespread institutional adoption, allowing universities to tailor the platform to local pedagogical and linguistic needs [5].

Comparative analyses of LMS platforms such as Blackboard, Canvas and Sakai consistently rank Moodle among the most flexible and cost-effective systems for higher education institutions [10]. Its pedagogical capabilities include asynchronous and synchronous communication, collaboration spaces (forums, wiki pages and workshops), tools for formative and summative assessment, and detailed analytics for tracking student progress [12]. Furthermore, Moodle's open-source ecosystem encourages continuous community-driven innovation, which is consistent with institutional goals of sustainability and academic autonomy.

At the same time, research warns that Moodle's potential remains untapped when its implementa-

tion focuses primarily on administrative functions rather than promoting student-centred learning [8]. The pedagogical challenge therefore lies not in technological capabilities, but in designing learning experiences that encourage interaction, reflection and authentic assessment. This is consistent with the findings of North American and Western European universities, where the strategies for introducing digital technologies increasingly emphasise the design of learning and the competences of educators rather than simply introducing platforms [16].

1.4 Institutional context and rationale for the study

In Slovenia, the University of Ljubljana (UL) has committed to a systematic digital transition, guided by its Digital Strategy 2024–2027, which aims to improve the quality of teaching, research capabilities and social engagement through the use of digital technologies [17]. The Digital Strategy is aligned with the European vision of inclusive and sustainable digital education. Its goal is to strengthen the quality of teaching through the systematic development of digital competences among students and staff, while ensuring equal access and innovative pedagogical practices. The Faculty of Natural Sciences and Engineering is part of this process, as it systematically integrated Moodle into its study programmes back in 2017 as part of the institutional project Digital UL – Towards Excellence through Innovative Use of ICT [18], [19]. This integration has enabled the creation of a unified and secure learning environment accessible to all faculty members and students, for which teachers and students have also been provided with training and individual support.

Based on the university's strategic commitment, further development projects between 2021 and 2024 within the framework of the Development Pillar of Funding (RSF) and the ULTRA project for a sustainable society have encouraged the upgrading the use of Moodle online classrooms through interactive content, innovative assessment and collaborative learning activities. These initiatives directly respond

to international evidence that effective digital transformation requires ongoing institutional support, educator training and user-centred design [3, 10].

Accordingly, this study explores the experiences of students at the Faculty of Natural Sciences and Engineering in using Moodle-supported online classrooms. More specifically, it explores the perception of usability, communication, collaboration and assessment within the platform to identify both the strengths and challenges of current practice. By placing local findings within global discussions on digital pedagogy and user experience, this research contributes to the understanding of how institutional strategies can transform technological infrastructure into meaningful learning.

2 Methodology

The data on the use of online classrooms were for research purpose collected in two ways, i.e. by using built-in tools that allow administrators to capture data and with a student survey conducted at the end of an academic year among the students of all bachelor's and master's degree study programmes at the Faculty of Natural Sciences and Engineering, University of Ljubljana (UL NTF).

1.5 Data collection using Moodle built-in tools

The UL NTF online classrooms are hosted on the Moodle platform managed by the Digital Centre UL (<https://ucilnica-ntf.uni-lj.si/>). Classrooms are available for all courses entered into the UL NTF student information system (VIS). The classrooms are synchronised daily with the VIS system, ensuring up-to-date and automatically synchronised data. The automatic synchronisation allows *inter alia* for the automation of online classroom creation, content transfer and storage, and enrolment of students and course instructors.

The collection of statistical information for analysing the usage of Moodle virtual classrooms and its features to compare the academic years 2022/2023

and 2023/2024 was conducted using built-in tools (i.e. course usage statistics, module usage statistics, reports usage and the accessibility toolkit). In both cases, the Moodle version was 4.3 and the PHP version supported was 8.2.19.

1.6 Student survey on use of online classrooms

1.6.1 Instrument origin and validity

The survey on the use of online classrooms was created in the program Arnes 1Ka (Centre for Social Informatics, University of Ljubljana). The student survey was adapted from the COLLES (Constructivist On-Line Learning Environment Survey) framework [20], which is a well-established instrument, validated internationally across higher-education contexts to assess relevance, reflection, interactivity, tutor support, peer support and interpretation within Moodle environments. We maintained its core construct structure and translated/adapted individual items to fit the context of the Faculty of Natural Sciences and Engineering (UL NTF). Validity and testing were conducted in earlier pilot phases (2019–2021), with a smaller cohort of students already being experienced in using Moodle. Feedback from those pilots informed wording adjustments and section sequencing in the final version used for 2022/2023 and 2023/2024 data collection.

1.6.2 Structure of student survey

The survey comprised 24 questions divided into sections, the description of which follows below.

- After the opening address, the participating students were asked whether they had used an online classroom during the academic year in question. The students who had not used online classrooms (0.6% in the academic year 2022/2023 and 3.0% in the academic year 2023/2024) were redirected to the end of the survey as they did not have the relevant experience to complete the survey in full.
- Students who had used the online classroom continued the survey to the next section, where

they were asked whether it was the first time they had used the online classroom. Those who did not use the online classroom for the first time ticked the number of courses they had used it for, after which they answered an open-ended question about the purpose for which they had used it.

- This was followed by two similar sections on the appearance and user experience of using online classrooms on a computer or mobile device (phone, tablet). In both cases, students indicated their agreement with the statements on a five-point Likert scale (1 – strongly disagree, 2 – disagree, 3 – neither agree nor disagree, 4 – agree, 5 – strongly agree), and optionally entered comments about the user interface of the online classroom they accessed on a computer or mobile device.
- This was followed by a section on the distribution of content or materials in the online classroom. Students again indicated their agreement with the statements on a five-point Likert scale and, if they wished, wrote a comment in an open-ended question.
- In the section that followed, students indicated their agreement on a Likert scale with the statements on the possibility to participate in the online classroom. The Likert scale was this time a six-point scale due to the inclusion of the option “we have not used the above mentioned”. Students were given the opportunity to write their comments in this section as well.
- Students were also asked about their opinion on the use of the online classroom for the submission and ongoing evaluation of practical courses, project seminars or other types of assignments. Similarly as in prior sections, students first indicated their agreement with various statements on the topic on a six-point Likert scale and were then given the possibility to write their comments in an open-ended question.
- Online classrooms can also be used for exams; hence, we were interested in students’ opinions

on the final evaluation/assessment in the online classroom (quiz/exam). We again included a six-point Likert scale with different statements and enabled comments.

- This was followed by closed-ended questions to find out whether students had been using other software tools (e.g. Teams, Toom, Wbebx etc.) in addition to the online classroom.
- In the last section, students indicated the study programme they were attending and their gender.

The survey was active from 27 May–27 August 2023 in the academic year 2022/2023 and from 4 January–28 June 2024 in the academic year 2023/2024. Teachers included the link to the survey in the online classroom of their course. Students completed the survey on their own free will. No personal data was collected in the survey.

1.6.3 Target-group refinement and representativeness

Earlier pilot versions involved students from only a subset of programmes (mainly those with longer Moodle experience). The final two-year implementation expanded to include all bachelor’s and master’s study programmes at UL NTF, thereby encompassing both experienced and first-time users of online classrooms. This progression was intentional – by covering the entire population, the study captures a broader spectrum of digital-competence levels and user experiences, which would not have been observable in the initial, more homogeneous cohorts.

The number of students completing the survey in each academic year is shown in Figure 1. A total of 307 students participated in the survey over two academic years, with an average of 22.7% male and 77.4% female students (Figure 1). In the academic year 2023/2023, students from 10 study programmes participated in the survey, and in the following year, students from 15 study programmes of both bachelor’s and master’s degree study programmes (NB: UL NTF runs 16 bachelor’s and master’s degree study programmes), 22.9% of students being from

textile and clothing study programmes. The online classroom was used in the academic year 2022/2023 by 99.4% of the students surveyed, with a slight decrease in the proportion in 2023/2024 (97.4%), which may be due to the higher number of study programmes where some teachers do not use the on-line classroom, but were still included in the survey.

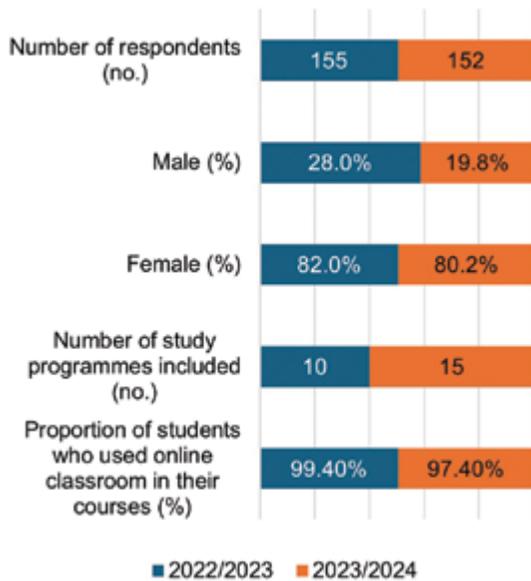


Figure 1: Number of respondents, proportion of respondents by gender and number of study programmes in which survey was conducted in academic years 2022/2023 and 2023/2024

1.6.4 Statistical analysis

Some of the results obtained from the Likert scale (ordinal data) were statistically analysed – the Wilcoxon signed-rank test was used for dependent samples and the Wilcoxon rank-sum test was used for independent samples.

3 Results

1.7 Activities in online classrooms

The data in Table 1, collected using Moodle's built-in tools, show that the number of activities in the academic year 2023/2024 increased compared to 2022/2023, particularly in the uploading files such

as text documents, image materials, videos, presentations etc.

Table 1: Number of activities, files uploaded to Moodle classrooms and users registered with mobile devices in academic years 2022/2023 and 2023/2024

Number of activities/ documents/users	Academic year		Difference (%)
	2022/2023	2023/2024	
Number of activities	4.903	5.413	10.40
Number of files	117.117	173.752	48.36
Word document	1.269	1.752	+38.06
PDF document	15.541	20.985	+35.03
Presentation	534	676	+26.59
Video document	2.055	2.158	+5.01
Audio file	90	88	-2.22
Pictures	32.355	54.517	+15.62
Number of users with registered mobile devices	116	255	119.83

The general trend of mobile device usage is also reflected in the study process (119.83% compared to 2022/2023) as depicted in Table 1.

In the survey, students pointed out that they mainly used online classrooms to review materials uploaded by the teacher (hence the significant increase in uploaded documents to online classrooms in Table 2), to submit seminar papers, project assignments, reports etc., to join groups, take quizzes and

Table 2: Number of used modules in Moodle classrooms in academic years 2022/2023 and 2023/2024

Module	Academic year		Difference (%)
	2022/2023	2023/2024	
File	1446	1942	+34.30
Forum	1028	705	-31.42
Assignment	611	661	+8.18
Folder	337	479	+42.14
URL	377	424	+12.47
Page	292	243	-16.78
Text and media area	209	172	-17.70
Quiz	185	144	-22.16
Book	60	78	+30.00
PDF Annotation	8	75	+837.50
Group choice	28	31	+10.71
H5P	19	30	+57.89
Choice	18	20	+11.11

surveys, participate in forums, take ongoing tests and final exams, to read and receive messages, and to monitor information. Table 2 shows data on the usage of Moodle modules between the academic years 2022/2023 and 2023/2024.

Table 2 shows that in the academic year 2023/2024, there was an increased use of several modules, indicating that teachers started using Moodle online classrooms more regularly. This is particularly evident in the increased number of uploaded files, use of URL links, folders, books, PDF annotations, group selections, H5P and other activities. We can certainly conclude that the effort invested in training and conducting numerous training sessions, online workshops and webinars is paying off, as this not only improves computer literacy among the educational staff but also among all students, technicians and other external collaborators at the Faculty of Natural Sciences and Engineering.

1.8 Student survey results in academic years 2022/2023 in 2023/2024

1.8.1 Basic information on use of online classrooms

The results of the surveys conducted in the academic years 2022/2023 and 2023/2024 are shown below.

Figure 2 shows that the proportion of students using an online classroom for the first time increased in 2023/2024, as did the average number of courses in which students used an online classroom, namely from 4.5 classrooms/student in 2022/2023 ($s = 2.04$) to 5.2 classrooms/student in 2023/2024 ($s = 2.76$). The increase in the proportion of first-time users of online classrooms was expected, as teachers of courses that had not used online classrooms before also started using them. Consequently, students then also used online classrooms for the first time.

As already mentioned in the Introduction, the increased use of online classrooms resulted from the active entry of UL NTF into two important projects in 2021 and 2022, i.e. the ULTRA 2.01 project. Both projects included training and workshops for the staff, which contributed to raising the digital com-

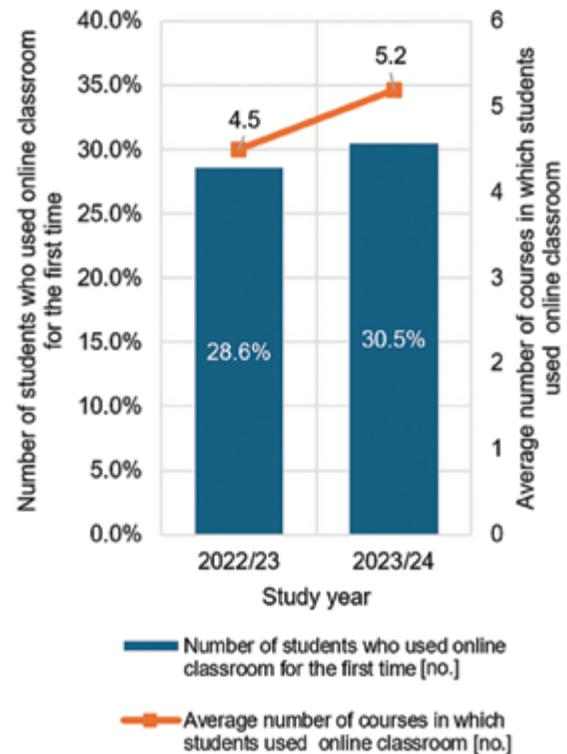


Figure 2: Proportion of students using online classroom for the first time and average number of courses in which students used online classroom in academic years 2022/2023 and 2023/2024

petences of teachers and significantly increased their confidence in using online classrooms.

In addition to online classrooms, teachers also used other software in their courses (Figure 3). They used MS Teams in a higher proportion (the use of this tool even increased by 10.2% in 2023/2024), Zoom for remote conversations (the use of this tool decreased by 25.9% in 2023/2024) and some Google tools such as Drive, Forms etc. We attribute the use of these tools to different reasons. MS Teams was used by the majority of teachers at UL NTF during the Covid era and they got used to it; hence, some of them still do not want to replace this tool with online classrooms. They mainly use MS Teams for uploading materials, meetings and remote consultations etc. They also add that uploading materials by students to MS Teams is easier, since the teacher does not have to open additional functionalities for students to upload files as it is the case in online classrooms

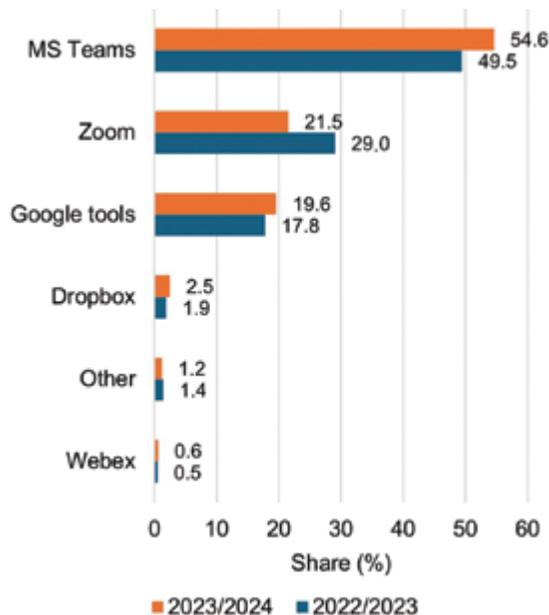


Figure 3: Use of additional software tools in online classrooms in academic years 2022/2023 and 2023/2024

(e.g. assignment etc.). Zoom is mostly used for online meetings and conversations; however, in the last year, it was frequently replaced by MS Teams. Google tools were widely used at UL NTF before the Covid era; nevertheless, their use has been decreasing year by year, being replaced mainly by MS Teams. Other software tools that are still used in very small proportions are Dropbox, Webex, OneDrive and WeTransfer. Although institutional strategies have promoted the integration of online communication within learning management systems, e.g. Moodle, students still prefer communicating with their instructors by email rather than through LMS forums or messaging tools. This pattern appears to be influenced not only by technological usability but also by social and pedagogical factors. Research shows that email is often perceived as a more personal, direct and reliable communication channel, enabling students to receive prompt responses while maintaining a sense of privacy and control. Moodle-based forums are often associated with public exposure and formality, which may discourage students from posting questions visible to peers. In addition, the ergonomic design and notification settings of LMS communication tools

can hinder user engagement. Furthermore, students' habits frequently mirror teachers' own communication practices – when instructors primarily respond by email or fail to model the use of forums, students perceive Moodle as an administrative rather than dialogic environment.

1.8.2 Appearance and user experience of online classrooms on computers and mobile devices (phone, tablet)

As Figure 4 shows, the proportion of students using the online classroom on computers decreased in the academic year 2023/2024 compared to 2022/2023, while online classrooms were more frequently accessed on mobile devices, esp. phones (the increase in the use of online classrooms on phones is also reflected in the data in Table 1).

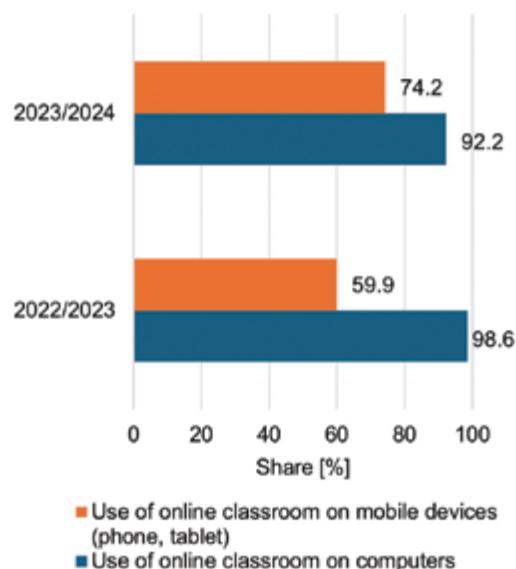


Figure 4: Use of online classrooms on computers or mobile devices (phone, tablet)

In the academic year 2022/2023, the Centre for Digital University of Ljubljana (CDIUL) introduced a new interface for the online classroom, which was to enable easier access and, in particular, viewing content on mobile device. Figures 5 and 6 show the results of the user experience of students who used the online classroom on computers and mobile

devices, respectively. The scores are calculated from the proportions of Likert scale ratings from 1 to 5. In the 2022/2023 survey, 15.9% of respondents an-

swered “neither agree nor disagree” to the questions about the user experience, compared to 17.5% in 2023/2024.

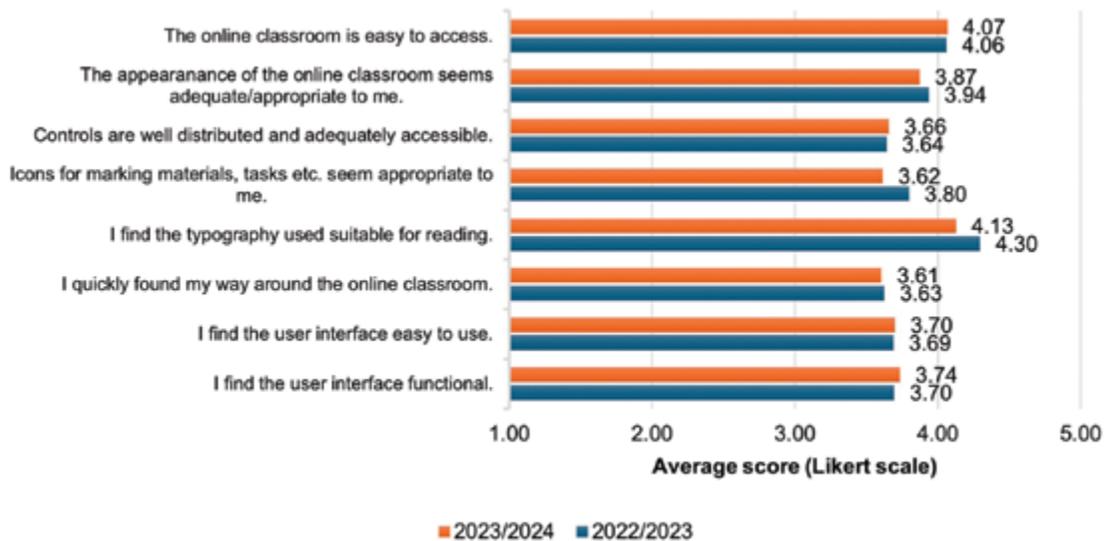


Figure 5: User experience ratings of online classroom on computer (Likert scale: 1 – strongly disagree, 5 – strongly agree)

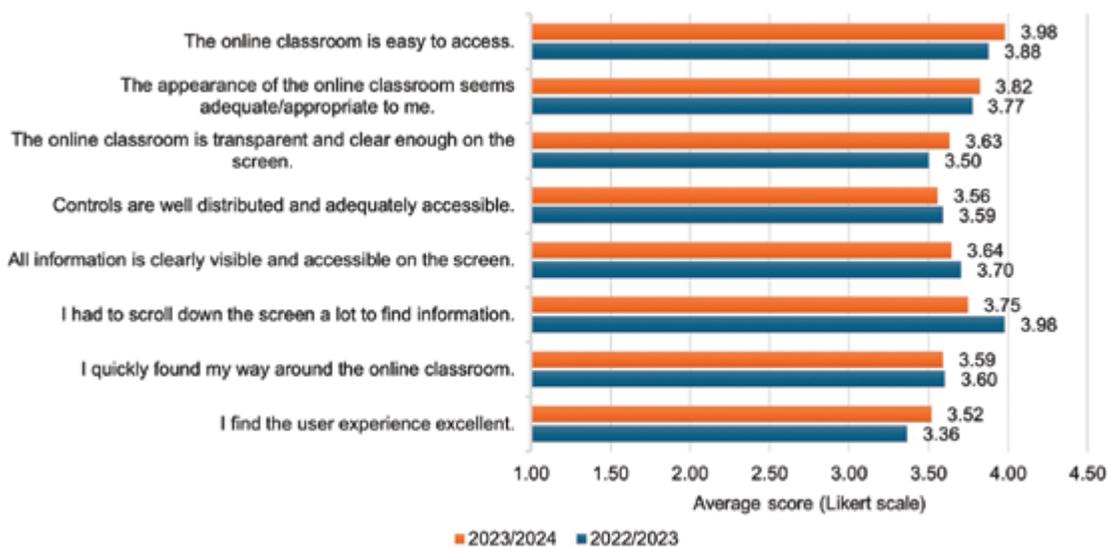


Figure 6: User experience ratings of online classroom on mobile devices, i.e. phone, tablet (Likert scale: 1 – strongly disagree, 5 – strongly agree)

Students found it easier to access the online classroom on a computer than on mobile devices. The results of the Wilcoxon signed-rank test indicated a statistically significant difference in accessibility

to the online classroom on a computer and a mobile device for both academic years 2022/23 ($Z = -3.01$, $p = 0.0026$, $r = -0.6$) and 2023/24 ($Z = -2.25$, $p = 0.0242$, $r = -0.5$). Among the comments about the

access on computers, the main difficulty highlighted was the difficulty to access the online classroom on some browsers (e.g. Firefox), while some students had difficulty accessing the online classroom on mobile phones due to the constant reminder to redirect to the Chrome browser.

The online classroom appearance on a computer and on mobile devices was rated by students as adequate/appropriate. However, the results of the Wilcoxon signed-rank test indicated that for the academic year 2022/23, the difference in the online classroom appearance between a computer and mobile device was statistically significant ($Z = -2.89$, $p = 0.0038$, $r = -0.5$), while for the academic year 2023/24, the difference was not statistically significant ($Z = -1.65$, $p = 0.0972$, $r = -0.3$). Therefore, we cannot claim that the users noticed a difference in the appearance of the classroom on a computer or mobile device in the academic year 2023/24. Comments on the online classroom appearance included missing an interface more similar to the Apple experience, wanting more personalisation of the dashboard and better transparency.

Students were satisfied with the layout and accessibility of controls, both on computers and mobile devices. However, the results of the Wilcoxon signed-rank test indicated that for the academic year 2023/24, the difference in the layout and accessibility of controls in the online classroom on a computer and mobile device was statistically significant ($Z = -3.84$, $p = 0.0001$, $r = -0.7$), while for the academic year 2022/23, the difference was not statistically significant ($Z = -1.95$, $p = 0.0506$, $r = -0.3$). Therefore, we cannot claim that the users noticed a difference in the layout and accessibility of controls in the online classroom on a computer or mobile device in the academic year 2022/23. Nevertheless, there was a comment regarding the complex presentation of controls.

Although the reported satisfaction with the icons in the online classroom in 2023/2024 was slightly lower compared to 2022/2023 (a decrease of 4.86%), the Wilcoxon rank-sum test showed that this difference was not statistically significant

($p = 0.106$). A similar trend was observed in the satisfaction with typography, which also decreased slightly in 2023/2024 (by 3.92%). The Wilcoxon rank-sum test indicated no statistically significant difference in satisfaction with the typography used on the computer between the academic years 2022/2023 and 2023/2024 ($p = 0.3792$, $Z = 0.8794$). The decrease in satisfaction may be due to possible changes in the user interface. The evaluated non-statistically significant differences in both cases suggest that the observed decline may reflect normal variability in student responses rather than a significant change in their perceptions of the icons. Among the students' comments, there was a minor dissatisfaction with the terminology used (e.g. the terms "my courses" and "local courses").

While students found the information to be quite visible and accessible on mobile screens, it was relatively time-consuming to get to, requiring a lot of "scrolling". The dissatisfaction with the search process (and also about the difficulty of opening pdf files) increased in 2023/2024 (score was down by 5.78%). The results of the Wilcoxon rank-sum test indicated a non-statistically significant difference in the search process used on the mobile devices between the academic years 2022/2023 and 2023/2024 ($p = 0.0822$, $Z = 1.7381$). Given the small calculated standardised effect size ($r = 0.13$), it would be desirable to obtain a larger sample size per group.

Students agreed that the user interface of online classrooms was functional and easy to use, although a bit more for a computer than mobile devices, and that they quickly found their way around online classrooms. Despite some difficulties, they praised the practicality of online classrooms, as they could access them from anywhere, check new information and, in some cases, receive it to their email address.

1.8.3 Content distribution in online classroom

When evaluating the arrangement of content in the online classroom, it is important to bear in mind that the arrangement of content depends on the administrator (i.e. teacher) of the online classroom to decide

how and in what way to arrange different content. Of course, students' assessment can also be very subjective, as some students may prefer a certain way of

arranging the materials more than others. Therefore, the students' comments in this section of the survey were very varied, as indicated below.

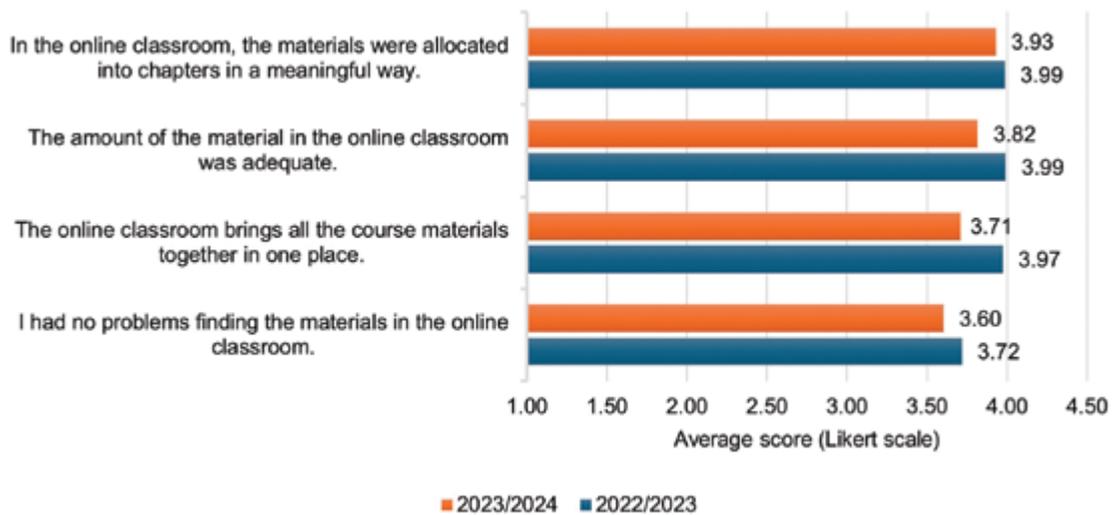


Figure 7: Content arrangement in online classroom (Likert scale: 1 – strongly disagree, 5 – strongly agree)

Figure 7 shows that students were satisfied with the meaningful separation of chapters in both academic years (scores 3.93 and 3.99). They were also satisfied with the amount of material and the possibility to have all the material in one place. We noted that the ratings for these two statements were slightly lower in 2023/2024, which can be attributed to the fact that a number of teachers were new to using online classrooms in this academic year, and may not yet be as proficient, while some were still using a combination of two platforms, e.g. online classroom and MS Teams.

Students gave slightly lower scores for searching for materials in the online classroom. Among the comments that need attention, the majority focused on the online classroom on mobile devices, namely that the presentations were not “clickable” and the already mentioned “scrolling” search on mobile devices (often cited as a problem), which can lead to confusion and lack of clarity as the user gets lost between chapters. Students also mentioned positive features of online classrooms, in particular that the material was in one place and did not have to be searched or downloaded from other platforms and

that they would like to see online classrooms in all courses.

The results of the Wilcoxon rank-sum test indicated that no statistically significant differences were found in any of the statements shown in Figure 7 between the academic years 2022/2023 and 2023/2024 ($p > \alpha$; $\alpha = 0.05$). The standardised effect sizes for all statements were small ($r \approx 0.10$ – 0.30); therefore, increasing the sample size per group would improve the likelihood of reliably detecting such small effects.

1.8.4 Possibility to collaborate (interact with teacher, teaching assistant and peers) in online classroom

Students rated the cooperation options on a five-point scale, where we added the sixth option “we have not used the above mentioned”. This also allowed us to obtain for each statement the proportion of students who used tools to interact with the teacher, teaching assistant and peers.

Table 3 shows that in both academic years, students most frequently used the course news monitoring via the forum or notifications uploaded/sent by the teacher. In a much lower proportion, students

used the online classroom for group work, usually for group assignment submissions, peer assessment, comments etc. The online classroom was the least

used for exchanging opinions or interacting with the teacher and/or teaching assistant, e.g. via the forum, chat or messaging.

Table 3: Percentage of students who used online classroom collaboration functionalities in academic years 2022/2023 and 2023/2024, and average scores obtained from Likert scale assessment (1 – strongly disagree, 5 – strongly agree)

Interaction possibility within online classroom	Usage percentage (%)		Average score (–) (Likert scale)	
	2022/2023	2023/2024	2022/2023	2023/2024
The online classroom allowed me to keep up to date with news in the course (e.g. via forum, notifications added to the classroom by the teacher and/or teaching assistant).	89.1	86.1	3.88	3.68
The online classroom allowed me to exchange opinions/ ideas (e.g. via forum).	62.5	54.6	3.35	2.88
The online classroom allowed me to interact with the teacher and/or teaching assistant (e.g. via forum, chat, messages).	64.8	62.0	3.32	3.18
The online classroom enabled group work with my peers (e.g. group assignment submission, forum posting, commenting and peer assessment).	76.6	71.3	3.48	3.17

From the average ratings of the interactions given, it is generally observed that the ratings relating to the possibilities to participate in the online classroom are on average lower for all statements given, except for following the course news. Students' comments indicated that they prefer using other platforms/tools for peer-to-peer communication, while they prefer communicating with teachers by email, as it is perceived to be faster. Nevertheless, students' comments praised the possibility to be informed, as they received messages sent by some teachers from the online classroom to their email addresses (e.g. notifications about assignment due dates, assignment submission, comments on assignments etc.), consequently keeping them up to date with everything that was happening in the course. They would like to be informed from one source rather than several (e.g. higher education student information system – VIS, email, MS Teams, Google applications etc.), which was disruptive in some courses.

The scores for 2023/2024 were lower than the previous year for all statements. We do not have an exact answer as to why the scores decreased; however, we can again assume that both teachers and

students had not yet mastered all the collaborative functionalities offered by online classrooms, given that many of them were using the online classroom for the first time.

The results of the Wilcoxon rank-sum test indicated that no statistically significant differences were found in any of the statements shown in Table 3 between the academic years 2022/2023 and 2023/2024 ($p > \alpha$; $\alpha = 0.05$). The standardised effect sizes for all statements were small ($r \approx 0.10$ – 0.30); therefore, increasing the sample size per group would improve the likelihood of reliably detecting such small effects.

1.8.5 Submission and ongoing evaluation of products of practical courses, seminars, projects or other types of assignments

In the case of the submission and ongoing evaluation of students' work, we also first determined the extent to which the functionality was available to them. Table 4 shows that in both academic years, online classrooms were most frequently used for the submission of assignments completed at practical courses, projects etc. In slightly lower proportions, students also received feedback from teachers and

grades for the assignments submitted in online classrooms. Online classrooms were often used also for group assignment submissions.

Table 4: Percentage of students who participated in submission and ongoing evaluation functionality of online classrooms in academic years 2022/2023 and 2023/2024

Interaction possibility within online classroom	Usage percentage (%)	
	2022/2023	2023/2024
Ongoing submission of tutorials, seminars, projects and other assignments	95.5	88.1
Teacher and/or teaching assistant reactions to submitted assignments	85.0	75.2
Group submission of assignments at practical courses, seminars, projects	82.0	78.0
Submitting assignments at practical courses, seminars, projects on forum	85.0	74.3
Monitoring grades in the online classroom and performance on required assignments at the course	83.5	78.0

Figure 8 demonstrates that the online classroom is a suitable place to submit the assignments completed at practical courses, seminars, projects and elsewhere. Students also agreed that submitting assignments to the online classroom is easy and that group submission is useful. They also had a similar opinion about the monitoring of assignment grades,

which is, according to the score, useful. Students also liked the fact that they could submit assignments to the online classroom on an ongoing basis, as this made it easier for them to meet deadlines and the feedback from the assessors allowed them to improve their products in terms of quality.

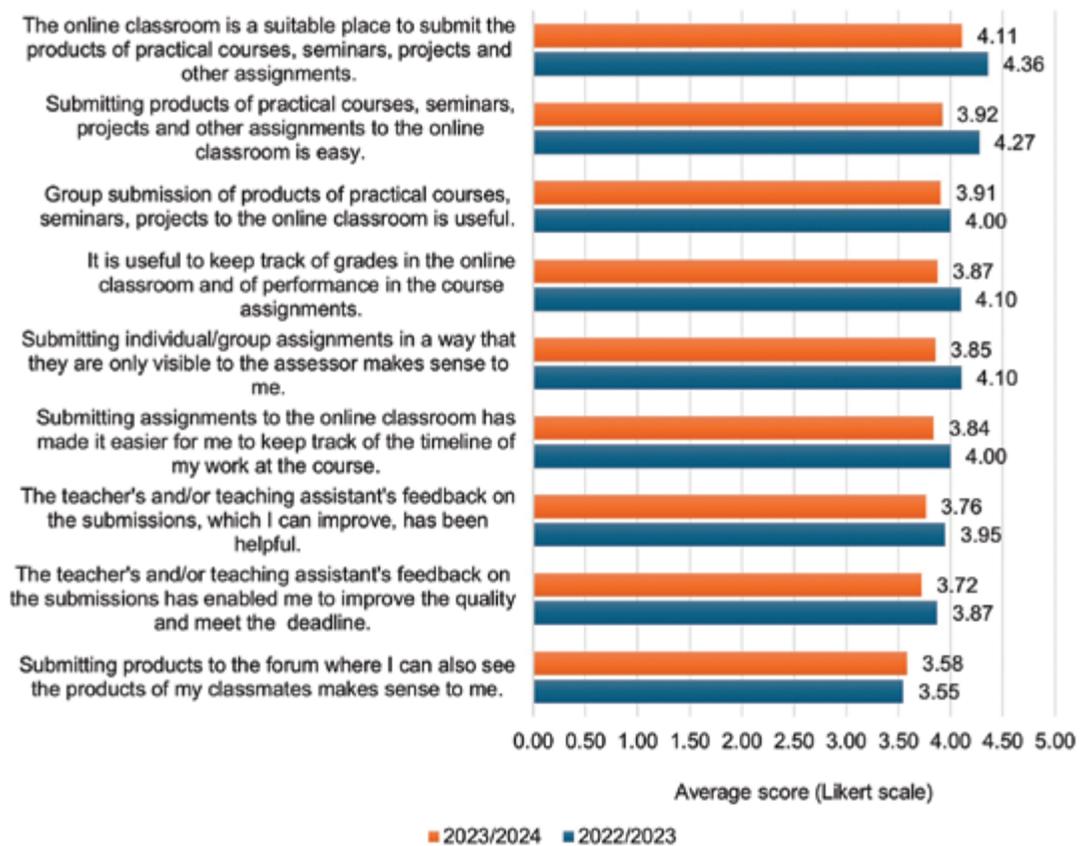


Figure 8: Possibility to participate in online classroom (Likert scale: 1 – strongly disagree, 5 – strongly agree)

Similarly as in the previous case of cooperation, the scores were lower in 2023/2024 compared to the previous year. The online classroom is a place with a number of functionalities to facilitate work, and monitor student work and progress. These functionalities must be mastered by the teacher and brought to the attention of students, who can then build on and complement their work. From the students' comments, we established that teachers often do not review or grade the submitted assignments, and as a consequence, students do not get a response to the products they upload to the online classroom. Due to inappropriate settings, some students failed to submit assignments and some students complained about the amount of unnecessary information in the submission (e.g. too many unnecessary buttons, windows, steps etc.).

On the other hand, positive comments focused on the ease and convenience of submission, while students mostly received assignment grades by email or in person. The calendar, where submission deadlines are written down, and the general up-to-date information on submissions and submission deadlines were praised. The method of group submission was also highly appreciated.

The results of the Wilcoxon rank-sum test indicated that no statistically significant differences were found in any of the statements shown in Table 4 and Figure 8 between the academic years 2022/2023 and 2023/2024 ($p > \alpha$; $\alpha = 0.05$). The standardised effect sizes for all statements were small ($r \approx 0.10-0.30$); therefore, increasing the sample size per group would improve the likelihood of reliably detecting such small effects.

1.8.6 Final evaluation/exam assessment in online classrooms

The online classroom can also be used for final assessments – exams. This functionality, which is implemented via the Quiz plugin, was already used during the Covid era, while after the return back to classrooms, teachers have mostly abandoned this option, due to live exams, also due to the nature of the field of study, being more convenient. It is for the latter reason that the proportion of students who participated in this part was much lower (44.5% of students answered the questions in this part in 2022/2023 and 42.7% in 2023/2024). The rest had no experience with online classroom examinations.

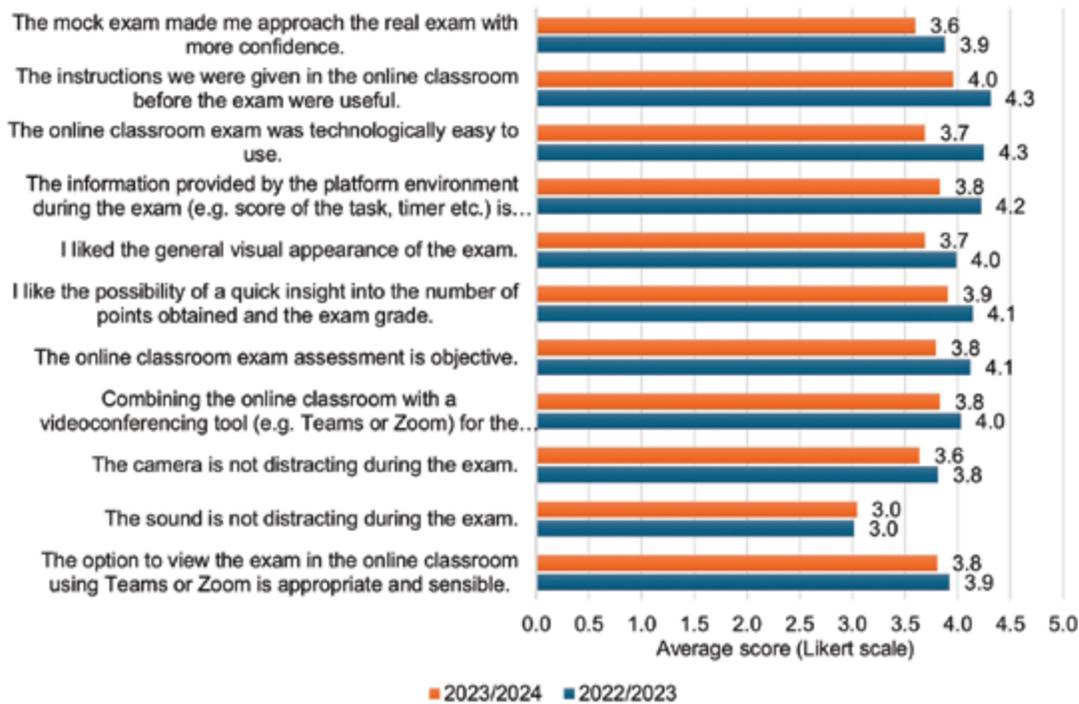


Figure 9: Final evaluation/exam assessment in online classrooms (Likert scale: 1 – strongly disagree, 5 – strongly agree)

As responses in Figure 9 show, students agreed that it is advisable to do a mock exam for the students to get used to the testing environment and the options it offers (moving around the test, type of test questions, re-answer options, question information etc.). The mock exam made students more confident in approaching the real exam.

Students agreed that instructions uploaded by the teacher in the form of a document or a note to the online classroom were useful. The instructions described the exam process, the equipment required to write the exam (e.g. a good internet connection, a working camera and microphone), the rules for writing etc.

Students mostly had no problems during the exam, except for the Firefox browser, which caused some problems (interruptions, inability to access etc.) especially in the academic year 2023/2024. They agreed that the implementation was technologically simple, the information provided by the exam environment (quiz) was useful and that the appearance of the exam itself was pleasant. However, there were a few remarks, e.g. that the names of some of the "buttons" were not understandable or were difficult to link to the function it provided.

The exam requires a combined use of the online classroom with a videoconferencing tool (e.g. MS Teams, Zoom). Students found this combination suitable. They were not disturbed by the camera being switched on during the exam; however, they found the sound more distracting, as they could hear the sounds of typing on the keyboards, possible background noise etc.

Students liked the fact that they had a quick overview of their scores and exam grades after the exam, and they felt that the assessment itself was objective.

Through additional comments, the online classroom was mostly praised, saying that it was a good way of conducting the exam, that it enabled a more relaxed atmosphere etc. However, there were also a few comments that it was easier to write the exam in person, that the exam time was too short and that they were nervous about sitting the exam online.

We noticed that in the academic year 2023/2024, there were fewer negative comments about the implementation of exams in the online classroom environment; however, students did have more problems with the equipment (mainly cameras not working, connecting via phones etc.) and with interruptions of exams mostly due to browser difficulties. The problems with the cameras were exclusively students' problems, while the problem with browsers is a systemic problem that will have to be solved at the level of the technical service.

The results of the Wilcoxon rank-sum test indicated that no statistically significant differences were found in any of the statements shown in Figure 9 between the academic years 2022/2023 and 2023/2024 ($p > \alpha$; $\alpha = 0.05$). The standardised effect sizes for all statements were small ($r \approx 0.10$ – 0.30); therefore, increasing the sample size per group would improve the likelihood of reliably detecting such small effects.

4 Conclusion

The findings of this study indicate that the digital transformation at the Faculty of Natural Sciences and Engineering has gone beyond the administrative integration of Moodle into course management processes and has begun to influence pedagogical practices at several levels.

The increase in the number of uploaded materials and active classrooms reflects not only administrative compliance but also a growing trend towards blended learning. Students gain continuous access to resources, which supports self-regulated learning and flexible study pacing, a core principle of constructivist pedagogy emphasised in our theoretical framework [4, 8].

High engagement with the Assignment and Quiz modules indicates a gradual move from summative assessment towards formative evaluation. Students' comments highlight that receiving feedback on uploaded work improved the iterative development of projects, supporting reflective and process-oriented learning. This suggests that digital

tools are increasingly used to facilitate continuous assessment loops, consistent with the European Commission's Digital Education Action Plan [1, 2].

While the use of forums and peer-assessment features remains lower than expected, their inclusion in course design demonstrates pedagogical awareness of collaborative learning. Students' remarks that teachers rarely engage in forum-based dialogue underline a need for stronger teaching presence, as proposed in social-constructivist models. These insights reveal that the main challenge is no longer technical implementation, but the pedagogical activation of digital spaces.

Increased mobile device access reflects changing study habits and confirms the importance of inclusive, mobile-first learning design. Students' mixed experiences with interface navigation suggest that UX factors directly influence engagement and motivation, an often-overlooked pedagogical dimension of usability.

The results of online examinations and submission-based tasks indicate that students view digital environments as authentic extensions of classroom learning when clear instructions and transparent grading are provided. This aligns with the TAM model, where perceived usefulness and clarity increase acceptance and learning confidence [7, 5].

As mentioned already, Digital Centre UL has started developing a new user interface for online classrooms. The upgrade is planned as part of the RSF project Unified plug-in and customised interface of online classrooms at the University of Ljubljana, where mentors and students from our faculty are participating. According to the present research, the results obtained can represent the starting point for the redesign and creation of an effective user interface and the creation of an integrated learning environment.

Future studies will examine teachers' technological pedagogical and content knowledge (TPACK) to assess how these competences influence the effective and pedagogically grounded use of Moodle in higher education. They will also focus on peda-

gogical outcomes, exploring how improved online classroom design and functionality influence student engagement, learning retention and academic performance, thereby linking digital transformation more directly with educational impact.

Regardless of further research, we can make recommendations for broader and more effective use of Moodle at the faculty, based on the results obtained so far. Recommendations may include systematic training for both teaching and technical staff on more advanced Moodle features, encouraging the use of interactive tools, developing unified pedagogical guidelines for designing online course environments, regularly monitoring student satisfaction and user experience and integrating their feedback, introducing incentives for teachers who actively develop digitally supported teaching etc. Such recommendations would not only strengthen the conclusion but also contribute to more strategic planning of the faculty's future e-learning development.

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Optimizing Fashion E-Commerce: The Impact of Quick Delivery, Sustainable Practices and Competitive Pricing on Customer Satisfaction and Delivery Efficiency

Optimizacija modnega e-trgovanja: vpliv hitre dostave, trajnostnih praks in konkurenčnih cen na zadovoljstvo strank in učinkovitost dostave

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Abstract

This study investigates the interplay between customer satisfaction, delivery efficiency, pricing strategies, ESG (environmental, social and governance) sustainability practices and quick third-party delivery systems within the fashion e-commerce sector. The findings reveal that quick third-party delivery services significantly enhance customer satisfaction ($\beta = 0.135, p < 0.001$) and improve delivery efficiency through strategic partnerships with providers such as Blinkit and Rapido ($\beta = 0.651, p < 0.001$). The adoption of ESG sustainability practices, such as e-bikes and e-rickshaws as a mode of transportation, has a significant impact on quality assurance for sustainable deliveries ($\beta = 0.684, p < 0.001$), which can be linked to customer satisfaction and brand recognition. This research emphasizes that customer satisfaction plays a mediating role in the linkage of delivery efficiency to pricing strategies ($\beta = 0.789, p < 0.001$), bridging operational performance to cost-effectiveness. Moreover, technology adoption moderates the relationship between eco-friendly delivery assurance and customer satisfaction ($\beta = 0.191, p < 0.001$), while with accessible and user-friendly digital platforms, sustainable practices have more impacts. These results underscore the need for expedient, sustainable and customer-centric delivery approaches that address evolving consumer needs. This research can provide insights to achieve long-term customer loyalty and sustainable growth with global sustainability objectives.

Keywords: fashion e-commerce, customer satisfaction, ESG sustainability, quick delivery services, pricing strategy, delivery efficiency, sustainable logistics, third-party delivery

Izvleček

Študija raziskuje medsebojno povezanost med zadovoljstvom strank, učinkovitostjo dostave, strategijami določanja cen, trajnostnimi praksami ESG (angl. Environmental, Social and Governance; slo. okoljski, socialni in



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upravljavski vidiki) ter hitrimi dostavnimi sistemi preko tretjih oseb v sektorju modnega e-trgovanja. Rezultati kažejo, da hitre dostave preko tretjih oseb pomembno vplivajo na zadovoljstvo strank ($\beta = 0,135$, $p < 0,001$) in izboljšujejo učinkovitost dostave preko strateških partnerstev s ponudniki, kot so Blinkit in Rapido ($\beta = 0,651$, $p < 0,001$). Uvedba trajnostnih praks ESG, npr. uporaba električnih koles in električnih rikš kot prevoznega sredstva, ima pomemben vpliv na zagotavljanje kakovosti trajnostnih dostav ($\beta = 0,684$, $p < 0,001$), kar se lahko povezuje z zadovoljstvom strank in prepoznavnostjo blagovne znamke. Raziskava poudarja, da je zadovoljstvo strank vmesni člen med učinkovitostjo dostave in strategijami določanja cen ($\beta = 0,789$, $p < 0,001$), pri čemer je operativna učinkovitost povezana s stroškovno učinkovitostjo. Sprejemanje novih tehnologij ravno tako vpliva na odnos med zagotavljanjem okolju prijazne dostave in zadovoljstvom strank ($\beta = 0,191$, $p < 0,001$), pri tem pa imajo trajnostne prakse z dostopnimi in uporabniku prijaznimi digitalnimi platformami še močnejši vpliv. Izsledki raziskave poudarjajo potrebo po hitrih, trajnostnih in na stranke usmerjenih pristopih k dostavi, ki odgovarjajo na spreminjajoče se potrebe potrošnikov. Raziskava nudi predloge za doseganje dolgoročne zvestobe strank in trajnostne rasti v skladu z globalnimi trajnostnimi cilji.

Ključne besede: modno e-trgovanje, zadovoljstvo strank, trajnost ESG, hitre dostavne storitve, strategija določanja cen, učinkovitost dostave, trajnostna logistika, dostava preko tretjih oseb

1 Introduction

In the rapidly evolving fashion industry, innovative technologies are significantly transforming customer experiences. One such advancement, virtual reality (VR), is garnering increasing attention as a transformative tool, offering immersive platforms for presenting fashion exhibitions [1, 2]. Traditionally, fashion has been defined by its visual appeal and tactile engagement. Omnichannel marketing is an advanced online selling strategy that provides customers with a seamless experience across multiple channels, including physical storefronts and online platforms [3]. This multi-channel sales strategy unifies the buying experience across physical stores, smartphone apps and social platforms, providing customers with a consistent and integrated experience. Technological advancements have enabled retailers to engage in novel ways with customers, such as using social media networks like Instagram and Facebook to reach a wider audience and showcase products effectively [4]. This increases their likelihood of becoming brand ambassadors for you in addition to increasing the likelihood that they will visit your store again and make another purchase. This may include building a more valued

clientele, which would increase your company's total profitability [5]. Business models that increasingly use current technologies and evolving customer behaviour compel entrepreneurs to enhance their innovative capabilities to remain competitive [6–7]. This assessment reveals the adequacy of the provided service quality [8]. Ultimately, customer satisfaction is a function of service quality, which is evaluated based on the user's experience and perception of the service delivered [8]. However, satisfaction is not solely determined by service quality. Additional influencing factors include brand image, advertising effectiveness and consumer trust, especially in online environments where concerns over cybersecurity and fraud remain prevalent [9]. Enterprises in this domain often compete based on the level of customer satisfaction achieved through their products and services [10–11].

1.1 Background study

1.1.1 Strategies for improving customer satisfaction

Strategies for enhancing customer satisfaction vary depending on a company's products or services, available resources and the characteristics of its

customer base. The transparent communication of shipping policies, estimated delivery times and proactive updates via email or SMS (especially in cases of delays) builds trust and manages expectations. Finally, product and service quality encompass more than just the physical attributes of an item. It extends to production processes, packaging, marketing and after-sales service, all contributing to overall customer satisfaction [12]. Quality is closely tied to the efficiency of supply chain operations, playing a pivotal role across manufacturing, logistics and customer service functions [13].

1.1.2 Enhanced customer satisfaction

Effective and responsive online customer service plays a critical role in enhancing customer satisfaction. This proactive approach not only minimizes customer frustration but also demonstrates that the business values its customers. As a result, customers are more likely to develop positive perceptions of the brand and recommend it to others, contributing to a more satisfying and holistic user experience.

Increased sales and repeat business

Providing excellent customer service has a direct impact on purchasing behaviour and customer retention. Quality service fosters trust and reliability, making customers feel confident in their decisions. This trust can transform one-time buyers into loyal repeat customers, thereby boosting long-term sales and contributing to the development of a dedicated customer base.

Enhanced brand reputation

The quality of customer service significantly influences a brand's reputation. Positive experiences often lead to favourable online reviews and word-of-mouth referrals, which can attract new customers. In contrast, negative service encounters may harm a company's image and deter potential buyers. A strong reputation for delivering exceptional customer service differentiates a business from competitors and supports sustained growth in a competitive online marketplace.

Valuable customer insights

Customer service interactions provide valuable data regarding customer needs, preferences, and pain points. Analysing feedback from complaints, support tickets and suggestions helps identify recurring issues and areas for improvement. These insights can provide information for product development, refine marketing strategies and enhance overall service quality. Businesses that actively use customer feedback to tailor their offerings are more likely to exceed expectations, stay ahead of competitors and foster deeper customer engagement.

1.2 Research objectives

- a) To analyse the impact of quick delivery systems and third-party partnerships on customer satisfaction within the online fashion retail sector.
- b) To evaluate the role of logistics tie-ups, such as with Blinkit and Rapido, in enhancing delivery efficiency and ensuring secure site deliveries for fashion retailers.
- c) To examine the influence of environment, Social, and governance (ESG) sustainability practices, including the use of e-bikes and e-rickshaws, on quality assurance in eco-friendly delivery options.
- d) To investigate the mediating role of customer satisfaction in the relationship between pricing strategies (e.g., discounts and budget-friendly offers) and safe site delivery efficiency.

This shift in consumer behaviour and technology has led to a more efficient and innovative business model [14]. Additionally, this research aims to assist customers in calculating and identifying their clothing size during shopping, while examining the impact of fast fashion on traditional retail, considering five fashion entities, three of which are fast fashion and two retail industries [15]. This research also provides a comprehensive understanding of the fast fashion industry's implications on the retail industry [16].

1.3 Research Hypothesis

H1:	Quick third-party delivery systems significantly influence customer satisfaction
H2:	Logistics tie-ups significantly enhance safe site delivery efficiency for fashion retailers.
H3:	ESG sustainability practices significantly influence quality assurance for eco-friendly delivery.
H4:	Customer satisfaction mediates the relationship between pricing strategies (discounts and budget-friendly offers) and safe site delivery efficiency.
H5:	Technology adoption (ease of use and accessibility) moderates the relationship between customer satisfaction and quality assurance for eco-friendly delivery.

Hypothesis 1: Quick third-party delivery systems significantly influence customer satisfaction, presented an index system for assessing customer satisfaction with third-party logistics service quality [17]. It uses original data to create a questionnaire based on the evaluation index. This study reveals that logistics service speed is the most significant factor affecting customer satisfaction, while risk perception is the least important. This paper aims to improve logistics service satisfaction for online shopping, while examining the impact of short delivery times on product returns in online retailing. It uses a large dataset from a global fashion retailer's US online selling platform. Results show that fast deliveries increase the likelihood of returns, especially among new customers. Using the Unified Theory of Acceptance and Use of Technology (UTAUT) model, it found a significant correlation between omnichannel shopping and satisfaction [18-19]. With 85 respondents, the data was analysed using SPSS tools and statistical tools such as frequency and regression analysis.

Hypothesis 2: Logistics tie-ups significantly enhance safe site delivery efficiency for fashion retailers explored the impact of delivery efficiency on online shoppers' relationships with e-retailers [20-21]. This review, based on 70 studies, highlights challenges such as order volume, inventory tracking and timely shipping. To overcome these, companies can invest in infrastructure, inventory management, transportation systems and emerging technologies such as drones and robots.

Hypothesis 3: ESG sustainability practices significantly influence quality assurance for eco-friendly delivery explored the role of innovation and online selling models in sustainable development, particularly in Dubai [22]. It discusses strategies such as green sourcing, efficient production, smart inventory management, sustainable warehousing, green transportation, eco-friendly packaging and reverse logistics [23]. This paper also reviews existing literature on intelligent logistics management, sustainability in attended home delivery and public views on online selling.

Hypothesis 4: Customer satisfaction mediates the relationship between pricing strategies (discounts and budget-friendly offers) and safe site delivery efficiency investigated online selling managers' pricing strategies to understand their motivations and challenges [24]. This study finds that personal perspectives and judgments are more complex and difficult to measure than economic factors. Online selling owners often struggle with determining a suitable pricing strategy due to intangible product value. By creating a high usability website for phone cases and related products, 42 individuals were tested with regard to their purchasing behaviour. Results showed no correlation between the effectiveness of selling strategies and perceived usability

Hypothesis 5: Technology adoption (ease of use and accessibility) moderates the relationship between customer satisfaction and quality assurance for eco-friendly delivery. Product development is crucial for business operations, especially in the fashion

industry. With advancements in technology and environmental awareness, sustainable product development processes (PDPs) are essential identified supply chain structures that identify essential steps in fashion PDPs, classify them into traditional, new and sustainable processes, and analyse key factors for sustainable fashion using the triple bottom line framework [26–27].

2 Material and Methods

2.1 Research design

The research design serves as the foundational framework for this scientific study. It outlines a strategic plan that guides the researcher in answering research questions and testing the proposed hypotheses. A comprehensive research design ensures all components of the study are logically and cohesively

integrated to effectively address the research problem. A well-structured design is vital for ensuring the accuracy, reliability and validity of the research, while each stage must be meticulously executed to achieve meaningful outcomes.

2.2 Conceptual framework

The conceptual framework in this study illustrates the interrelated elements that influence customer satisfaction and delivery efficiency in the fashion online selling sector. The integration of advanced technologies further enhances service quality by enabling real-time tracking, automation and data-driven decision-making. Together, these elements create a synergistic model aimed at meeting evolving customer expectations, boosting satisfaction and improving delivery performance in the competitive fashion e-commerce landscape.



Figure 1: Conceptual framework

2.3 Data collection tools and techniques

A questionnaire using Likert-scale questions was used to assess respondents' impressions of delivery dependability, environmental and social responsibility, price equity and technology adoption. It also collected demographic data, such as age, gender and purchasing frequency, to provide deeper insights into customer preferences and behavioural patterns. The study participants consisted of 390 respondents, all of whom were active online consumers with previous experience in acquiring fashion goods via online selling platforms. Individuals who had

not engaged in online fashion purchases over the preceding six months were omitted from the sample to ensure relevance.

2.4 Measures

Data was gathered with the help of a structured questionnaire. The questionnaire was prepared using a Likert-type scale where respondents were asked to share their opinions regarding various research questions under study. The questionnaire included a set of both open-ended and closed-ended questions. Questions were carefully crafted to gather meaningful

information with respect to identified research variables. There were five categories of respondents in the survey, while a separate questionnaire was designed for each category of respondents.

2.4.1 Quick third-party delivery systems

Quick third-party delivery systems are crucial for enhancing product delivery speed and efficiency in online selling. These systems use third-party logistics providers to ensure goods reach customers quickly, impacting customer satisfaction and sales performance. Implementing quick delivery systems in fashion online selling is essential for staying competitive in the fast-paced market. This study assessed the effectiveness and timeliness of these systems using a 5-point Likert scale, assessing reliability, efficiency, timeliness, customer satisfaction and overall performance in the online selling environment.

2.4.2 Logistics tie-ups

Logistics tie-ups are strategic collaborations between fashion online selling companies and third-party logistics providers to improve supply chain efficiency, delivery timelines and operational costs. This study focuses on the impact of logistics tie-ups on customer satisfaction and operational performance. A 5-point Likert scale was used to assess the effectiveness of these partnerships in streamlining delivery processes, ensuring timely shipments and contributing to customer satisfaction. The scale gauged stakeholders' perceptions of the efficiency and reliability of logistics tie-ups in the fashion online selling sector.

2.4.3 ESG sustainability practices

In this study, ESG sustainability practices include strategies, policies and actions to reduce environmental impact, promote social equity and ensure ethical governance. A scale was used to evaluate a company's commitment to these practices, measuring environmental impact, social responsibility and governance practices. The scale used a 5-point Likert scale, with responses corresponding to each of the three ESG pillars, ranging from strongly disagree to strongly agree.

2.4.4 Customer satisfaction

Customer satisfaction is the satisfaction customers feel when their expectations and needs are met by a company's products or services. Factors influencing customer satisfaction include product quality, delivery efficiency, pricing strategies and overall purchasing experience. A 5-point Likert scale was used to measure satisfaction levels, with respondents indicating their level of agreement or disagreement. The scale gauged satisfaction with aspects such as product quality, delivery timeliness, ease of purchase and value for money.

2.4.5 Safe site delivery efficiency

Safe site delivery efficiency is the efficient and safe delivery of goods or services to a designated site, ensuring timely completion and minimizing risks. This study used a 5-point Likert scale to assess this efficiency, focusing on delivery timeliness, safety adherence, resource management, risk mitigation and overall satisfaction with the delivery process. The goal is to ensure secure and efficient delivery without compromising safety.

2.4.6 Quality assurance

Quality assurance is a systematic process to ensure products, services or outcomes meet defined standards and objectives. It involves identifying, addressing and preventing defects or performance variations. Measures include monitoring, evaluating and improving processes. This study used a 5-point Likert scale to assess satisfaction, reliability and effectiveness, ensuring participants' perceptions are accurate. The scale ranges from strongly agree to strongly disagree.

2.4.7 Pricing strategies

Fashion online selling businesses use pricing strategies to determine product value and maximize sales and profitability, while considering customer preferences and market conditions. These strategies include dynamic pricing, discounting, bundling and value-based pricing. A pricing strategy scale assesses

perceived value, pricing fairness, price sensitivity and competitive pricing using a 5-point Likert scale with five questions. Participants indicate their level of agreement with pricing strategies.

2.4.8 Technology adoption

Technology adoption is the process of accepting and implementing new technological innovations, which is crucial for organizational growth and operational efficiency. This study used a technology adoption scale to assess these factors, focusing on perceived ease of use, usefulness, compatibility with existing systems and attitude towards technology. A 5-point Likert scale with five questions was used to analyse how technology adoption affects organizational performance and individual engagement with new technologies.

3 Results and discussion

This study investigates how pricing strategies, ESG sustainability practices and quick third-party delivery systems contribute to customer satisfaction and safe site delivery efficiency in the fashion online selling sector. This research also explores the impact of partnerships with logistics companies such as Blinkit and Rapido on delivery performance, alongside the role of eco-friendly delivery options, such as e-bikes and e-rickshaws, in improving quality assurance for sustainable delivery. Additionally, it examines how technology adoption moderates the relationship between eco-friendly delivery and customer satisfaction, and how customer satisfaction mediates the link between pricing strategies and safe site delivery efficiency. Data were collected via structured questionnaires from stakeholders in the online fashion selling sector, offering valuable insights into balancing cost, sustainability and customer satisfaction in delivery procedures.

The constructs demonstrate excellent reliability and validity, with Cronbach’s alpha values ranging from 0.820 to 0.896, confirming strong internal consistency. Convergent validity is established, as all

Table 1: Internal consistency and convergent validity

Variables	Cronbach's Alpha	CR	AVE
Quick third-party delivery systems	0.892	0.865	0.785
Customer satisfaction	0.820	0.794	0.608
Logistics tie-ups	0.841	0.876	0.822
Safe site delivery efficiency	0.850	0.871	0.805
ESG sustainability practices	0.896	0.866	0.788
Quality assurance for eco-friendly delivery	0.840	0.827	0.676
Pricing strategies	0.846	0.870	0.802
Technology adoption	0.842	0.875	0.819

AVE values exceed 0.5. Composite reliability (CR) values are also above the 0.7 benchmark, thereby reinforcing the constructs’ dependability. ESG sustainability practices and logistics tie-ups exhibit exceptionally high reliability and validity, laying a robust foundation for further analysis of inter-variable relationships.

Table 2: Descriptive statistics of variables

Variables	Mean	Std. deviation
Quick third-party delivery systems	3.7446	0.76559
Customer satisfaction	3.7328	0.69600
Logistics tie-ups	3.6544	0.69202
Safe site delivery efficiency	3.6926	0.72707
ESG sustainability practices	3.7015	0.79222
Quality assurance for eco-friendly delivery	3.7072	0.77060
Pricing strategies	3.6215	0.72796
Technology adoption	3.6600	0.69014

Respondents displayed generally favourable perceptions of all variables, with means ranging from 3.6215 to 3.7446. Pricing strategies had the lowest mean, suggesting moderate satisfaction with discounts and competitive pricing. Quick third-party delivery systems received the highest mean, underscoring the need for efficient delivery in the fashion

online selling space. ESG sustainability practices showed the highest standard deviation (0.7922), indicating diverse opinions regarding the necessity for environmentally friendly logistics. Conversely,

technology adoption had the lowest standard deviation (0.6901), suggesting a consensus on the utility and accessibility of tech solutions.

Table 3: Discriminant validity

Variables	Quick third-party delivery systems	Customer satisfaction	Logistics tie-ups	Safe site delivery efficiency	ESG sustainability practices	Quality assurance for eco-friendly delivery	Pricing strategies	Technology adoption
Quick third-party delivery systems	0.886002							
Customer satisfaction	0.23	0.779744						
Logistics tie-ups	0.185	0.757	0.906642					
Safe site delivery efficiency	0.183	0.751	0.805	0.897218				
ESG sustainability practices	0.142	0.649	0.545	0.601	0.887694			
Quality assurance for eco-friendly delivery	0.165	0.686	0.617	0.665	0.677	0.822192		
Pricing strategies	0.178	0.789	0.685	0.709	0.68	0.67	0.895545	
Technology adoption	0.178	0.746	0.996	0.8	0.544	0.615	0.692	0.904986

Significant correlations ($p < 0.01$) indicate meaningful relationships among the constructs. Logistics tie-ups strongly correlate with technology adoption ($r = 0.996$) and safe site delivery efficiency ($r = 0.805$), suggesting these partnerships are essential for reliable deliveries. Pricing strategies strongly correlate with both customer satisfaction ($r = 0.789$) and delivery efficiency ($r = 0.709$), emphasizing the importance of strategic pricing. The square roots of AVE (diagonal values) confirm discriminant validity across constructs.

The results highlight key dynamics in fashion online selling. Quick third-party delivery systems significantly enhance customer satisfaction (H1), while logistics tie-ups critically improve delivery ef-

iciency (H2). ESG sustainability practices positively impact quality assurance in eco-friendly delivery (H3), validating their role in sustainable logistics. Furthermore, customer satisfaction acts as a strong mediator between pricing strategies and delivery efficiency, supported by high estimates.

Technology adoption moderates the link between eco-friendly delivery quality and customer satisfaction (H4), emphasizing how digital accessibility can amplify sustainable efforts. The consistent statistical significance ($p < 0.001$) strengthens the reliability of these findings.

The findings also reaffirm that service quality dimensions, such as reliability, responsiveness, empathy and tangibility, along with strong brand

Table 4: Hypothesis implementation

Hypothesis	Relationship	Estimate	C.R.	Sig. p	Results
H1	Quick third-party delivery systems → Customer satisfaction	0.135	2.459	***	Accepted
H2	Logistics tie-ups → Safe site delivery efficiency	0.651	12.326	***	Accepted
H3	ESG sustainability practices → Quality assurance for eco-friendly delivery	0.684	13.090	***	Accepted
H3	Mediating	0.789	25.302	***	Accepted
	Customer satisfaction → Pricing strategies				
	Safe site delivery efficiency → Pricing strategies	0.308	5.912	***	
	Safe site delivery efficiency → Customer satisfaction	0.508	9.749	***	
H4	Moderating				Accepted
	ZQuality assurance for eco-friendly delivery → ZCustomer satisfaction	0.191	5.028	***	
	ZQuality assurance for eco-friendly delivery → ZTechnology adoption	0.597	15.308	***	
	ZQuality assurance for eco-friendly delivery → INTERACTION	0.120	3.080	0.002	
Correlation is significant at the 0.01 level (2-tailed).					

trust, are critical to sustained customer satisfaction. Quick and eco-friendly deliveries, aligned pricing strategies and responsible governance frameworks are no longer optional; they are essential for long-term growth and loyalty in the online selling space.

4 Conclusion

This study investigates the key factors influencing customer satisfaction and safe site delivery efficiency within the fashion online selling industry, focusing on pricing strategies, logistical partnerships, ESG sustainability practices and rapid delivery methods. The findings offer valuable insights into how these elements interact and affect operational performance and customer satisfaction.

A key outcome reveals that swift third-party delivery systems significantly enhance customer satisfaction ($\beta = 0.135, p < 0.001$). The study emphasizes the importance of integrating quick delivery mechanisms to meet consumer expectations and ensure a positive online shopping experience. Stra-

tegic collaborations with platforms such as Blinkit and Rapido were also found to significantly improve delivery efficiency at safe sites ($\beta = 0.651, p < 0.001$), minimizing logistical challenges for fashion retailers.

ESG sustainability practices emerged as a crucial factor in ensuring quality and environmentally responsible deliveries ($\beta = 0.684, p < 0.001$). Utilizing eco-friendly transportation methods such as e-bikes and e-rickshaws not only aligns with customer preferences but also bolsters brand image, highlighting the growing relevance of sustainability in e-commerce operations.

This research highlights the mediating role of customer satisfaction in the relationship between safe site delivery efficiency and pricing strategies. The strong mediation effect ($\beta = 0.789, p < 0.001$) indicates that customer satisfaction bridges the gap between operational effectiveness and cost-efficient pricing, influencing both purchase decisions and delivery performance.

The moderating impact of technology adoption on the relationship between eco-friendly delivery

assurance and consumer satisfaction is also significant. Accessibility and ease of use in digital platforms enhance the effectiveness of sustainable delivery methods, with notable moderating ($\beta = 0.191$, $p < 0.001$) and interaction effects ($\beta = 0.120$, $p = 0.002$). This underscores the importance of incorporating advanced technological solutions to foster loyalty and enrich customer experience.

The study demonstrates that quick third-party delivery systems, strategic logistics partnerships and ESG-aligned practices are critical drivers of customer satisfaction and delivery efficiency in the fashion e-commerce sector.

Future scope and limitations

Future research in the fashion online selling sector should delve into the role of emerging technologies, such as AI-driven logistics optimization, drone-based deliveries and blockchain, to enhance supply chain transparency. Additionally, there is significant scope for examining specific sustainability initiatives, including carbon-neutral shipping, eco-friendly packaging and the circular fashion economy, to better understand their impact on consumer perception and environmental outcomes. The participant demographics in this study may limit the generalizability of the findings across broader or diverse consumer segments, particularly in different geographical or socio-economic contexts. Furthermore, the study's focus on specific third-party logistics partnerships, such as recent collaborations between Reliance and platforms like Blinkit and Rapido, may not be universally applicable, especially in regions where such services are either unavailable or underdeveloped. These constraints suggest the need for future studies to incorporate a wider range of demographics and logistic models to ensure broader applicability and relevance.

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Data availability statement: Research data (survey questions and respondents' answers) contain sensitive participant information and cannot be anonymized without compromising the integrity and authenticity of the research. Therefore, the complete dataset can only be shared upon a justified request made directly to the corresponding author.

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