Sustainable Packaging User-centered Design Employing CycleGAN and Deep Learning

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An innovative approach was pursued for sustainable packaging design using Cycle Generative Adversarial Networks (CycleGANs), tailored for wood packaging engraving. The methodology includes four phases: user participatory design, assembly scheme design, detailed Finite Element Analysis (FEA) optimization, and computer numerical control (CNC) engraving production. Each phase targets sustainability from design to final product, minimizing environmental impact and economic costs. Emphasizing early user participation helps adapt designs to user needs and environmental standards. Innovations such as real-time updates of packaging patterns *via* cloud-based iterations and an FEA optimization system enhance durability and aesthetics. This approach improves the environmental footprint and recyclability of conventional wood packaging. The research aims to shift perceptions in the packaging industry towards more sustainable practices, showcasing the practical applications of advanced digital tools in traditional manufacturing. It offers a scalable model for integrating sustainability into packaging design, providing valuable insights and inspiring future innovations in environmentally friendly practices across the industry.

DOI: 10.15376/biores.19.4.7824-7841

Keywords: CycleGANs; User-centered design; Sustainable packaging design; CNC; Design for disassembly (DfD)

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INTRODUCTION

The urgency to implement sustainable practices within the packaging industry has emerged as a paramount concern, underscored by escalating environmental degradation and increasing consumer demand for eco-friendly products (Hillier *et al*. 2017; Monteiro 2019; Kozik 2020). Sustainable packaging design, which aims to reduce environmental footprints through resource efficiency and innovative material use, faces the dual challenge of maintaining functionality while minimizing ecological impact (Rajesh and Subhashini 2021; Lau and Wong 2024). The global push towards sustainability has placed the wood packaging and wood board manufacturing industries under scrutiny due to their significant resource consumption and waste generation (Sirviö *et al*. 2013; Friedrich 2022; Yu and Fingrut 2022). Traditionally, these industries have relied on methods that, despite being effective, contribute substantially to environmental degradation through the extensive use of virgin timber and high waste production. The advent of digital technologies presents a promising avenue to revolutionize the design, production, and recycling of wood products, potentially mitigating these impacts. As the demand for sustainable packaging solutions grows, the wood packaging and wood board sectors face increasing pressure to reduce their environmental footprints (Lee and Xu 2005). These sectors, crucial in logistics, transportation, construction, and furniture manufacturing, have historically driven deforestation and inefficient material use (Asim *et al*. 2022).

Design for Disassembly (DfD) is another critical approach in sustainable packaging design. It involves strategically selecting materials and design techniques that allow for easy assembly and disassembly, promoting a longer lifecycle for the materials used and facilitating easier recycling processes (Veerakamolmal and Gupta 2000). This approach is particularly beneficial in reducing waste and minimizing environmental impact, as it supports the circular economy model by allowing materials to be repurposed rather than discarded.

This research article examines the limitations of current practices within these industries, highlighting their inability to meet the critical needs for waste reduction, resource efficiency, and environmental conservation. It proposes a novel approach integrating digital fabrication technologies, such as Computer Numerical Control (CNC) routing and 3D printing, with advanced material science (Narayanan and Das 2014). These technologies improve the precision and efficiency of wood utilization and facilitate using recycled materials in new products, offering significant environmental, economic, and social benefits.

In this challenging landscape, advanced artificial intelligence (AI) technologies, particularly Generative Adversarial Networks (GANs) and, more specifically, CycleGAN networks, herald new possibilities for design innovation and sustainability (Almahairi *et al*. 2018; Creswell *et al*. 2018). CycleGANs, a subtype of GANs renowned for facilitating unpaired image-to-image translation, emerge as a potent tool for reimagining sustainable packaging design (Cabezon *et al*. 2022). Unlike traditional GANs that require paired datasets to learn translations between domains, CycleGANs can learn to convert images from one domain to another without direct correspondence, offering a groundbreaking approach to design transformation. This capability is particularly relevant for sustainable packaging, where the visualization of material substitutions and design modifications can be realized without extensive prototype development.

Given the recent literature highlighting the potential of AI to enhance design processes, the application of CycleGANs in sustainable packaging design remains an area ripe for exploration. This gap in research presents a significant opportunity for development, indicating the potential of CycleGANs to contribute to sustainability through innovative design alterations and material optimizations (Menon and Ranganathan 2022). By leveraging CycleGANs' unique ability to generate realistic packaging design alterations, this research explores avenues for reducing material use, enhancing recyclability, and promoting consumer engagement through visually appealing and functionally optimized designs.

Motivated by the potential of CycleGANs to catalyze a paradigm shift in sustainable packaging design, this research aims to investigate their application in creating more environmentally friendly and resource-efficient packaging solutions. By leveraging CycleGANs' unique ability to generate realistic packaging design alterations, this research explores avenues for reducing material use, enhancing recyclability, and promoting consumer engagement through visually appealing and functionally optimized designs.

This research aims to evaluate the effectiveness of CycleGANs in generating sustainable packaging user-centered designs and to assess their impact on the design process from conceptualization to prototyping. Specifically, the objectives of this research are: a) demonstrate how CycleGANs can facilitate the visualization of sustainable design alternatives, enabling designers to explore various eco-friendly packaging options without the need for extensive physical prototyping; b) optimize the use of biodegradable and recyclable materials in packaging designs, reducing reliance on non-renewable resources and minimizing environmental impact by integrating advanced digital technologies with sustainable design principles; c) develop a comprehensive database library specifically tailored for sustainability icons and design patterns, facilitating the seamless integration of sustainable practices by amateur and professional designers; d) employ Finite Element Analysis (FEA) to verify the structural integrity of packaging designs before fabrication, ensuring that they meet necessary durability and functionality standards.

Literature Review

Participatory design, user-centered design (UCD)

Participatory design is characterized by its democratic approach to the design process, where designers and users collaborate from the early stages. This collaboration ensures that the final product reflects the users' needs and preferences (Cipan 2024). Studies by Sanders and Stappers (2008) and Simonsen and Robertson (2012) have emphasized the value of this approach in democratizing design and fostering innovation through user engagement. These studies argue that participatory design can lead to more effective and satisfying outcomes, as it encourages the inclusion of diverse perspectives and knowledge bases. However, challenges such as managing diverse opinions and ensuring productive collaboration are also noted, underscoring the need for structured facilitation techniques.

User-centered design (UCD) takes a slightly different approach, focusing on placing users at the center of the design process through continuous feedback loops and iterative testing (Table 1). Norman (1986) laid the foundational principles of UCD, advocating for understanding user needs, behaviors, and contexts as the basis for design decisions. Literature in this domain frequently highlights the role of UCD in improving the usability and accessibility of packaging designs, leading to products that better meet consumer expectations. The emphasis on empirical user research within UCD is critical for grounding design decisions in real-world user experiences. However, integrating UCD into packaging design has challenges, including the potential for increased time and resource requirements due to iterative testing and revision cycles.

Table 1. Comparison of Participatory Design and UCD in Packaging Design

Aspect	Participatory Design	User-Centered Design (UCD)
Foundation	Co-creation with users, democratic approach	Understanding user needs through research and testing
Focus	Involving users as co-designers	Enhancing user experience and satisfaction
Strategies	Workshops, focus groups, collaborative sessions	Iterative testing, persona development, usability testing
Case Study Example	Eco-friendly packaging development through user workshops	Redesign of packaging based on usability tests and user

Co-creation extends the collaborative ethos of participatory design and UCD by involving users as consultants and active partners in the creative process. Prahalad and Ramaswamy (2004) introduced the concept of co-creation to leverage users' and designers' collective creativity and insights. In the context of packaging design, co-creation is lauded for its ability to generate innovative solutions that align with user desires and market needs.

Research by Füller *et al*. (2016) demonstrates how co-creation workshops can lead to break-through ideas in packaging design, bridging the gap between consumer expectations and technical feasibility. Yet, the literature also acknowledges the complexity of co-creating with users, including challenges related to intellectual property, equity in contribution, and the integration of co-created ideas into viable products.

A beverage company recognized the need to redesign its packaging to be more user-friendly and environmentally sustainable. The primary objectives were to improve the user experience through ergonomic design, enhance environmental sustainability using biodegradable materials, and maintain cost-effectiveness.

The redesigned packaging, made from biodegradable materials, featured an ergonomic shape for easier handling and a resealable cap to enhance usability and reduce spillage. User testing showed a 25% increase in user satisfaction regarding handling and overall design appeal. The case study demonstrated the value of integrating user-centered design with environmental sustainability in packaging design. Feedback from real users was crucial in guiding the design process, ensuring the final product met functional and aesthetic requirements and aligned with consumers' environmental values (Table 2).

This case study highlights the effectiveness of a user-centered approach in packaging design, particularly when combined with sustainability goals. The project underscores the importance of engaging with users throughout the design process and leveraging their insights to create solutions that are not only environmentally responsible but also highly attuned to user needs and preferences.

Table 2. Project Overview and Results

Stage	Activity	Outcome
User Research	Surveys and Focus Groups	Identified key user preferences and pain points
Design Prototyping	Creation of Multiple Prototypes	Developed prototypes based on user feedback
Usability Testing	User Interaction with Prototypes	25% increase in user satisfaction
Sustainability Analysis	Life Cycle Assessment (LCA)	Confirmed reduced environmental impact of new design

Notes: User Research: Conducted surveys and focus groups with target consumers to understand their preferences, pain points, and environmental values. Design Prototyping: Developed prototypes incorporating user feedback and sustainable materials. Usability Testing: Tested prototypes with users to assess ease of use, satisfaction, and design appeal. Sustainability Analysis: Performed a life cycle assessment (LCA) to evaluate the environmental impact of new packaging designs.

Sustainable packaging design

User-centered design (UCD) and sustainable packaging design represent two pivotal approaches in contemporary design, each addressing critical aspects of product development and environmental stewardship. While UCD focuses on tailoring design processes and outcomes to meet the needs and preferences of end-users, sustainable packaging design emphasizes minimizing environmental impact through innovative use of materials, production processes, and lifecycle considerations. The convergence of these approaches heralds a paradigm shift towards creating packaging solutions that are not only highly attuned to consumer desires but also embody the principles of ecological sustainability.

At the heart of user-centered design lies the philosophy that understanding user needs, behaviors, and contexts is crucial for creating products that offer meaningful and intuitive user experiences. This approach involves iterative design processes, including research, prototyping, testing, and refinement, to ensure the final product aligns with its intended audience's real-world needs and expectations. UCD champions the idea that a deep empathy for users can drive innovation, leading to functional and delightful products.

In parallel, sustainable packaging design challenges the traditional packaging paradigms by prioritizing environmental responsibility alongside functionality and aesthetics. This involves exploring materials that are recyclable, biodegradable, or de-rived from renewable resources, as well as designing for reduced material use and enhanced lifecycle efficiency. Sustainable packaging design seeks to address the growing environmental concerns related to waste and pollution, advocating for solutions that reduce the ecological footprint of packaging throughout its entire lifecycle—from production and use to disposal or recycling.

Integrating user-centered design with sustainable packaging principles presents a holistic approach that respects both the user and the environment (Table 3). It reflects an understanding that truly sustainable design solutions must resonate with users, encouraging adoption and fostering sustainable behaviors. By aligning user needs with environmental goals, designers can create packaging solutions that promote sustainability without compromising user satisfaction or product quality. This synergy enhances the user experience and contributes to broader efforts to combat environmental challenges, making UCD and sustainable packaging design critical components of responsible product development in the 21st century.

Table 3. Aspect Sustainable Packaging Design (Theory, Case Study, Design Method, Design Tools, Design Workflow, Design System)

Aspect	Sustainable Packaging Design
Theory	"Focuses on reducing environmental impact through the use of eco-friendly materials, efficient manufacturing processes, and designs that promote reuse and recycling. Theoretical frameworks often emphasize lifecycle analysis, material innovation, and the minimization of waste and carbon footprint."
Case Study	An example case study could involve a company redesigning its product packaging to be fully recyclable, utilizing biodegradable materials, and reducing packaging size to minimize waste. The case study would detail the process of material selection, design challenges, consumer response, and the environmental benefits achieved.
Design Method	Incorporates sustainable design principles from the outset, utilizing approaches like biomimicry, cradle-to-cradle, and circular design to inform decisions.
Design Tools	Employs tools such as lifecycle assessment (LCA) software, material innovation databases, and carbon footprint calculators to evaluate and optimize packaging designs for sustainability.
Design Workflow	Follows a structured process that begins with sustainability goals setting, followed by ideation, prototyping, testing, and refinement, with a continuous focus on environmental impact throughout.
Design System	Adopts a holistic view, integrating sustainable packaging design into the broader product development system, ensuring alignment with corporate sustainability objectives and compliance with environmental regulations.

Cycle Generative Adversarial Networks (CycleGANs) and deep learning (DL)

CycleGANs have emerged as a transformative tool in the design field, particularly for tasks requiring adapting and generating images across different styles or domains without needing paired examples (Zhang *et al*. 2020). The core mechanism of CycleGANs involve two sets of GANs—each consisting of a generator and a discriminator—working in tandem across two domains. For instance, in the context of packaging design, one might consider Domain A to represent traditional packaging designs and Domain B to encompass designs incorporating sustainable features. The first generator learns to translate images from Domain A to Domain B, while the second performs the inverse translation. The discriminators, meanwhile, strive to distinguish between real and translated images within their respective domains. The key innovation of CycleGANs lies in its introduction of a cycle consistency loss, which penalizes the model if an image translated from A to B and back to A again deviates significantly from the original image. This ensures that the learned transformations preserve the content of the images while altering their style to match the target domain.

The training process for CycleGANs is critical and requires a diverse and comprehensive dataset that spans a wide range of design styles and sustainability features (Wu *et al*. 2022). This diversity is crucial for the model to learn a broad representation of each domain, enabling it to generate more innovative and varied design options. However, compiling such datasets poses challenges, including ensuring a balanced representation of different design elements and sustainability attributes. Additionally, the iterative nature of model training necessitates continuous monitoring and adjustment to balance the trade-offs between innovation, practicality, and adherence to design constraints. This balancing act is essential for ensuring that the generated designs are novel, aesthetically pleasing, and viable from a production and environmental standpoint.

Deep learning complements CycleGANs by offering the capability to analyze complex patterns in user interactions and preferences (Yuan 2022). By applying deep learning models, designers can extract actionable insights from data on how users interact with packaging, what features they value, and how sustainable practices influence consumer behavior. These insights can then inform the CycleGANs training process, making packaging designs more likely to resonate with consumers and encourage sustainable behaviors. This synergy between CycleGANs and deep learning facilitates a more nuanced and user-focused approach to design, where a deep understanding of consumer preferences and sustainability considerations informs creative solutions. Integrating these technologies into the design process represents a powerful tool for designers seeking to innovate within practicality and environmental responsibility constraints.

EXPERIMENTAL

Methods

Integrating CycleGANs and deep learning into the design process represents an innovative approach to generating design options, particularly in user interaction and packaging design. This research proposed a workflow for sustainable packaging design and fabrication (SPDF) (Fig. 1), which consists of the following phases:

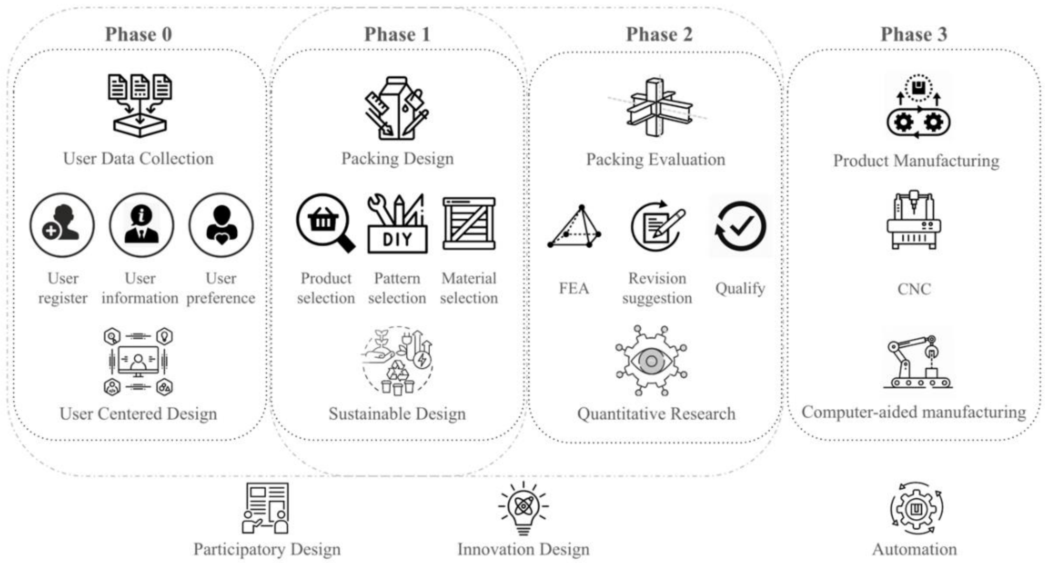

Fig. 1. A workflow from user data collection, packing design, packing evaluation, product manufacturing

Phase 0: User Data Collection

User data were collected from registration information and user preference surveys. This data generated user profiles to inform the design process.

Phase 1: Sustainable Packaging Design

Users participated as critical designers during the digital aggregation phase. They selected product types, sustainable patterns, and material types, contributing directly to the design process. Additionally, a comprehensive database library was developed to support sustainable design. This involved several steps: a) design of the database schema; b) data collection and entry; c) development of the user interface; d) implementation of access and security measures.

Phase 2: Packaging Evaluation

This phase involved evaluating the packing designs, focusing on user safety and packaging durability. The system detected and revised structural issues before fabrication, ensuring optimal performance.

Phase 3: Fabrication

Fabrication was conducted using Computer Numerical Control (CNC) machines. This method automated the control, movement, and precision of machining tools to carve surface wood textures for sustainable packaging.

Tools and Techniques Used

CycleGANs

CycleGANs facilitated the exploration of various design aesthetics and functionalities aligned with user-centered design and sustainable packaging principles. In the phase 0 of this research, a real-time and open-access database is provided to transfer 2D mapping target geometry (*e.g.*, packing box) for sustainable e-packing design (Fig. 2a).

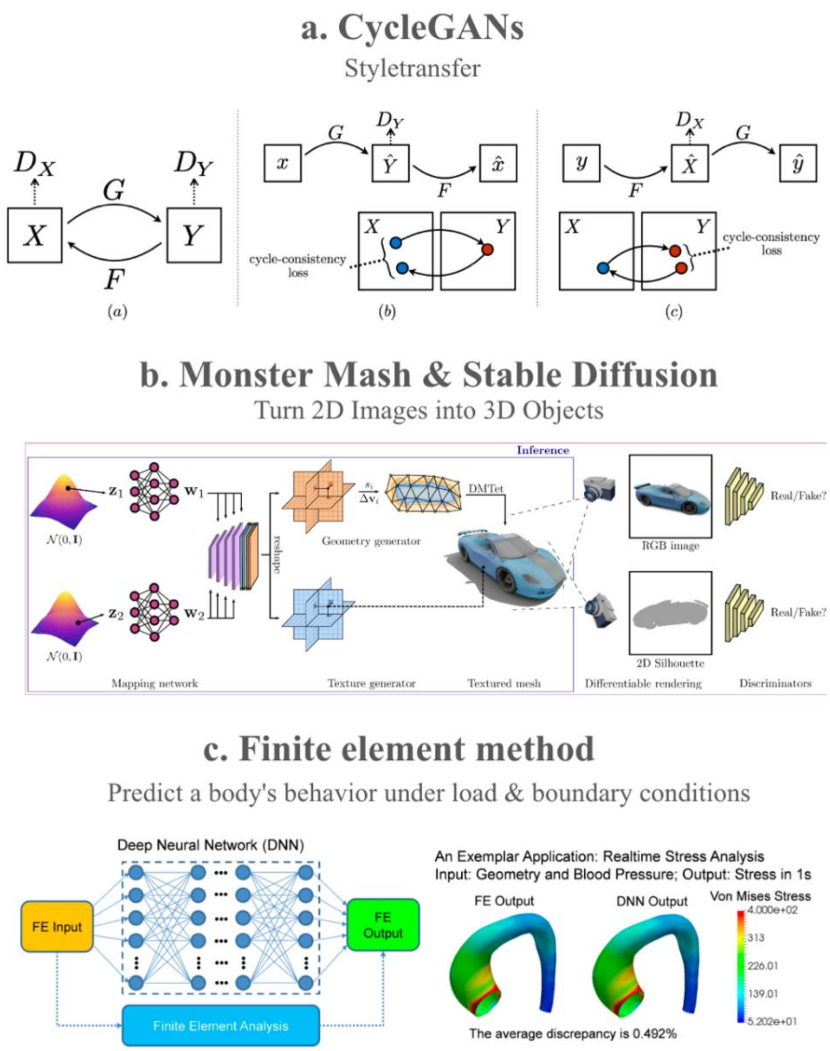

Fig. 2. a. CycleGANs– Design of style transfer; b. Stable Diffusion–Turn 2D Images into 3D Objects with Monster Mash; c. Finite element method

Stable Diffusion and Monster Mash

These deep learning models generated high-quality images from textual descriptions and simplified the creation of 3D models from 2D sketches (Rombach *et al.* 2022). Integrating Monster Mash and Stable Diffusion can revolutionize digital content creation, offering a seamless pipeline from 2D sketches to detailed 3D models generation enhanced by AI-driven text-to-image capabilities. In the phase 1 of this research, these two techniques are combined to turn 2D images into 3D objects (Fig. 2b).

Finite Element Analysis (FEA)

FEA is a computational technique used extensively in engineering to simulate and predict complex physical phenomena (Yu *et al.* 2023). By subdividing a large system into smaller, simpler parts called finite elements, the method approximates the equations that would be too difficult to solve analytically. In the phase 2 of this research, FEA is used to predict a body's behavior under load and boundary conditions (Fig. 2c).

CNC Machining

CNC technology was integrated with modern CAD/CAM software to streamline the production process. This method enabled the rapid transformation of digital designs into physical parts, reducing errors, optimizing material usage, and decreasing production time. In phase 3 of this research, CNC is used for automated high-precision carving of wood surface textures.

RESULTS AND DISCUSSION

Database and Interface

In the expanding field of sustainable design, integrating user interface/user experience (UI/UX) principles into DIY packing design tools represents a significant contribution toward enhancing user engagement and promoting environmental consciousness. This study delved into the development of a database library specifically tailored for sustainability icons and design patterns, aiming to facilitate amateur and professional designers' seamless integration of sustainable practices. The several strategic phases in developing this database library are crucial in ensuring the utility and success of the database in promoting sustainability through design (Fig. 3).

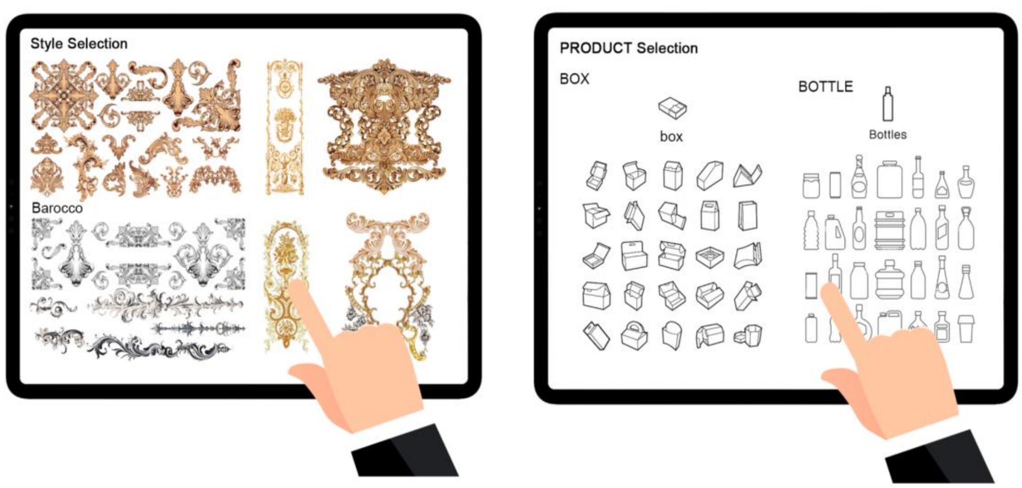

Fig. 3. User Design DIY process

Design of the database schema

The database schema was meticulously designed to organize various sustainability-related resources efficiently. It includes several tables: a. Icons Table: These stores icons related to sustainability themes such as energy efficiency, recycling, and sustainable materials. Each record includes fields for the icon ID, name, description, image file path, tags, date added, and source; b. Patterns Table: Similar in structure to the Icons Table, this table stores design patterns that advocate sustainable practices, with fields for pattern ID, name, description, pattern file path, and associated metadata; c. Tags Table: This table contains tags associated with themes prevalent in sustainability discussions to enhance searchability and categorization; d. Sources Table: Documenting the origins of each icon and pattern, this table includes source ID, name, description, and contact info, ensuring transparency and credibility of the content.

Data collection and entry

A rigorous data collection process was implemented to populate the database with high-quality, copyright-compliant icons and patterns from trusted sources. This process involved not only the gathering of images but also detailed descriptions and proper attributions to the original creators, ensuring respect for intellectual property rights and fostering a culture of acknowledgment in the design community.

Development of the user interface

The user interface supported robust search functionality, allowing users to locate resources efficiently by tags, names, or descriptions. Advanced filter options enabled sorting by categories, themes, or dates added. An optional user submission feature fostered a collaborative community atmosphere, further enriching the database with diverse contributions. Feedback indicated that these features significantly enhanced user experience and engagement, promoting a more interactive and user-friendly platform.

Implementation of access and security measures

A tiered access system was established to safeguard the integrity and exclusivity of the database, defining distinct levels of user interaction: guest, registered user, and administrator. Each level offers different permissions, enhancing the security framework of the database. Additionally, robust data protection measures were implemented to ensure that user information and database content remain secure against unauthorized access and potential breaches.

Preliminary feedback from users highlighted a significant enhancement in their ability to integrate sustainable practices into their design workflows. The database served as both a resource and an educational tool, raising awareness about sustainability issues through the very act of design. Users found that the availability of diverse and high-quality resources facilitated more informed and sustainable design choices, leading to better overall project outcomes.

Wood Packing Design, Design for Disassembly (DfD)

This research focuses on implementing DfD principles to create flexible, user-centric wood packing solutions that are both sustainable and practical. The findings reveal how varying wood types, joint techniques, and board selections can effectively enhance the disassembly and reusability of wood packaging (Fig. 4). A comprehensive database of materials and design elements was developed to support the design and selection process, providing designers and users access to a wealth of information on sustainable materials, design patterns, and construction techniques. This digital tool facilitated stakeholder communication, ensuring design decisions were informed by up-to-date, relevant data aligned with the latest sustainability practices.

Integrating DfD principles in wood packing design involves strategically selecting materials and design techniques that allow for easy assembly and disassembly, promoting a longer lifecycle for the materials used and facilitating easier recycling processes. This approach is particularly beneficial in reducing waste and minimizing environmental impact, as it supports the circular economy model by allowing materials to be repurposed rather than discarded. The joint design also plays a crucial role in DfD. Traditional woodworking joints such as dovetails, mortise, and tenon were compared against modern solutions such as clip and hook joints that can be easily engaged and disengaged without damaging the wood. The findings suggest that while traditional joints provide a sturdier build, they often complicate disassembly. In contrast, newer joint designs offer flexibility and ease of disassembly, aligning more closely with sustainability goals by supporting the reuse and recycling of materials.

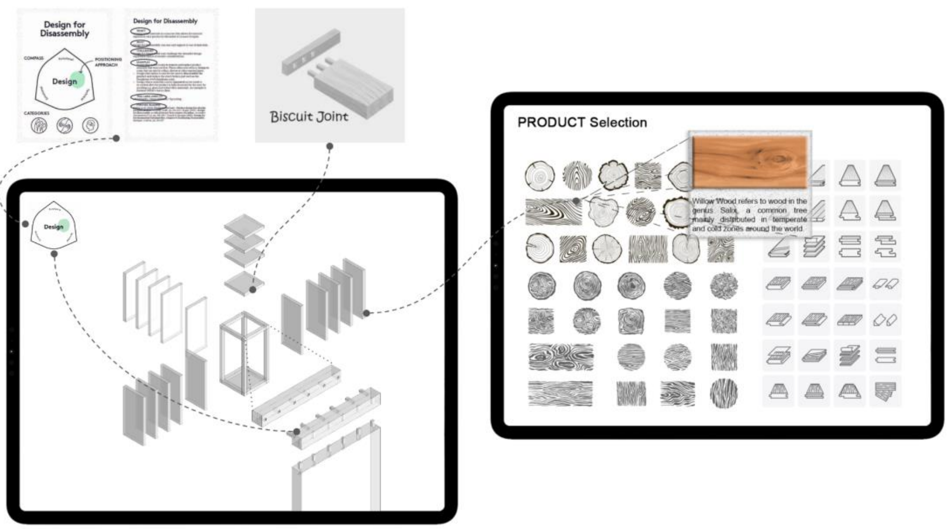

Fig. 4. Product selection and joints design

Furthermore, selecting wood types is central to the success of this design philosophy. The research evaluated various woods for their strength, durability, and ease of assembly/disassembly. Hardwoods and softwoods were assessed, with particular attention to how their physical and mechanical properties affect the overall design and functionality of the packaging. The results indicated that softer woods, while easier to manipulate and assemble, may not provide the long-term durability required for specific packaging applications. Conversely, hardwoods, known for their robustness, offer greater longevity but require more sophisticated joint techniques to facilitate disassembly. The choice of board types was explored, focusing on how different boards affect the structural integrity and disassembly of wood packaging. Plywood, particleboard, and fiberboard were tested, with evaluations based on their performance in various loading and environmental conditions. Plywood emerged as the optimal choice for applications requiring robust structural support, whereas particleboard and fiberboard were favored in situations where lighter weight and easier disassembly were prioritized.

The proposed method offers a holistic approach to sustainable packaging design that meets functional requirements and advances environmental and economic goals by optimizing material selection, joint design, user involvement and leveraging digital tools for data management and communication. This research contributes valuable insights to sustainable design and provides a solid foundation for future innovations in wood packaging.

Wood Packing Board FEA

In sustainable packaging, particularly in the wood packing industry, Finite Element Analysis (FEA) has emerged as a pivotal tool for optimizing wooden packing boxes' design and structural integrity before actual fabrication. This research employed FEA to simulate the behavior of wood materials under stress, using parameters reflective of typical wood properties, including linear elasticity, isotropic directional dependency, Young's modulus (E) of 1.2e+10 Pa, a Poisson's ratio (V) of 0.1, and a density (ρ) of 500 kg/m^3.

The results from the FEA simulations provide insights into the structural behavior and efficiency of wooden packing boxes (Fig. 5). By applying the linear elastic model, the research highlights how wood, despite its anisotropic nature, can be approximated as isotropic for simplification without significant loss of accuracy in this context. The chosen Young's modulus ensures that the wood's stiffness is modeled realistically, which is crucial for assessing the material's ability to withstand loads without permanent deformations. Similarly, Poisson's ratio used in the simulations affects the predictability of the lateral expansion or contraction of the wood as it is loaded, which is essential for designing joints and reinforcements in packing boxes. The FEA outcomes suggest that optimizing the wood's density in the design phase can lead to substantial cost savings and environmental benefits by reducing material use without compromising the structural integrity.

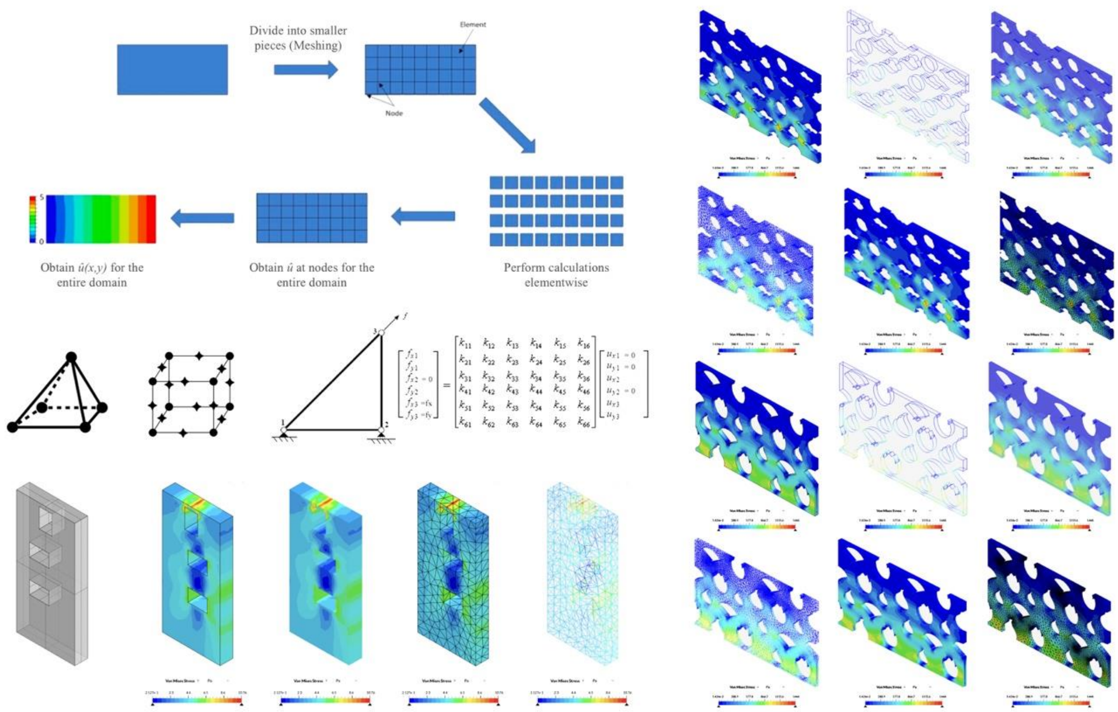

Fig. 5. Finite element analysis

Through these simulations, several design optimizations were identified. For instance, areas prone to high-stress concentrations could be reinforced using the strategic placement of supports or by altering the box's geometry, distributing the loads more evenly across the structure. This approach extends the packing boxes' lifespan and promotes material efficiency by preventing over-engineering. FEA also facilitated the exploration of different wood types and grades by virtually adjusting the material properties, such as Young's modulus and density. This capability allows for a more tailored design approach, where materials can be selected based on specific performance criteria and availability, further aligning the product design with sustainable practices; addressing these factors in the simulation phase aids in predicting potential failure modes and designing more resilient wood-packing solutions.

CNC Typology Making

Integrating CNC technology in wood packaging design represents a significant shift from traditional manufacturing methods, promising to revolutionize the industry by enhancing aesthetic appeal, precision, and efficiency. Traditionally, wood packaging production involved a series of labor-intensive steps: cutting logs or boards, cutting them into required lengths, assembling boards, nailing box boards, and finally assembling the boxes. However, the advent of CNC technology, particularly low-cost CNC machines suitable for industrial and engraving applications, has introduced a new paradigm characterized by automation, flexibility, and precision. Using CNC in wood packaging allows for the automation of cutting and assembly processes, utilizing computer control programs to execute complex design specifications with high accuracy. The research explored the capabilities of these CNC systems, noting their user-friendly interfaces, cost-effectiveness, and versatile operation. Particularly note-worthy is the application of laser engraving techniques facilitated by CNC, which enables intricate designs and patterns to be etched onto the wood surface, thereby enhancing the visual and aesthetic qualities of the final product (Fig. 6).

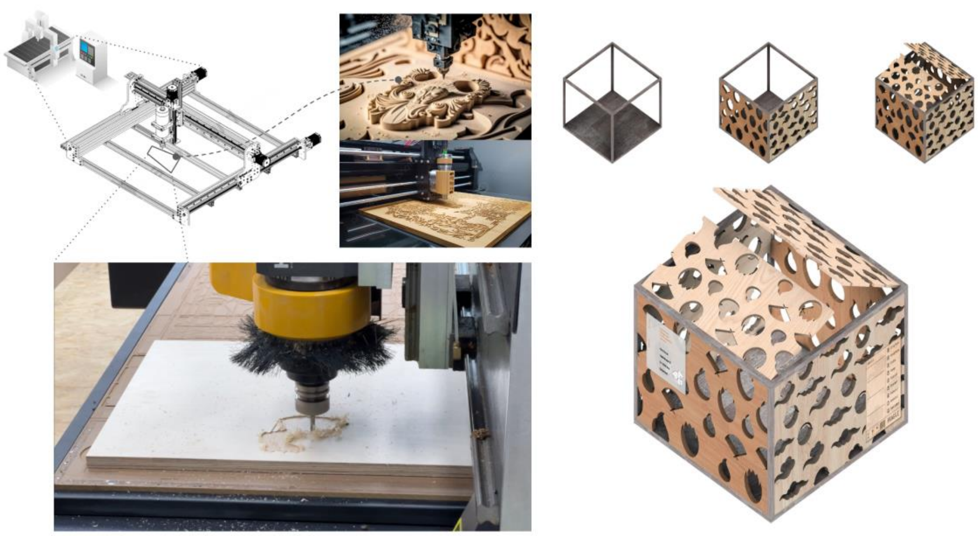

Fig. 6. CNC process

The empirical results from this research highlight a positive public response to CNC-produced wood packaging, which has a stronger aesthetic appeal than traditional craft products. This response is attributed to the precision and flexibility of CNC machines, which allow for high-fidelity reproduction of intricate two-dimensional patterns and designs on wooden surfaces. By applying these detailed engravings, wood packaging gains in visual appeal and market value, appealing to consumers and businesses looking for high-quality, aesthetically pleasing packaging solutions. The research examined the entire workflow of CNC in wood packaging production—from design conception to final construction. It was observed that laser engraving technology plays a crucial role in this process. Once the user selects a design plan, laser engraving is employed to precisely carve the design into the wood, ensuring that the finished product faithfully reflects the original specifications at a 1:1 scale. This capability ensures that the packaging meets functional standards and aligns perfectly with the intended design aesthetics, providing a seamless transition from digital designs to tangible products.

Integrating CNC technology into wood packaging design also aligns with broader industry trends toward sustainability and efficiency. CNC fabrication supports more sustainable production practices by reducing waste through precise cutting and minimizing the need for manual labor. Moreover, quickly and accurately producing custom designs on demand helps reduce excess production and inventory, aligning with just-in-time manufacturing principles. Adopting CNC and laser engraving enhances the aesthetic and commercial value of wood packaging and contributes to more sustainable and efficient manufacturing practices. As the industry continues to evolve, CNC technology is expected to play an increasingly central role in meeting the dual demands of market competitiveness and environmental responsibility. The findings from this research provide a compelling case for the continued integration of advanced manufacturing technologies in wood packaging production, offering insights that could guide future innovations in the sector.

DISCUSSION

Opportunities

Enhanced integration with user-centered design processes

Future research should focus on creating seamless interfaces between CycleGANs, deep learning (DL) models, and user-centered design methodologies. By developing tools that directly incorporate user feedback into the model training process, designers can rapidly iterate on product concepts more closely aligned with user needs and preferences.

Sustainability and material innovation

The potential for leveraging CycleGANs and DL to drive material innovation and promote sustainability in product design is vast. Future research could explore the use of these technologies to simulate and predict the environmental impact of different materials and manufacturing processes. This would enable designers to make more informed choices that reduce the ecological footprint of their products, thus advancing the field of sustainable design.

Customization and personalization

With growing consumer demand for personalized products, CycleGANs and DL can play a crucial role in enabling mass customization. Future developments might include DL models that automatically adjust designs based on individual user preferences or body measurements, offering a scalable approach to personalized product design.

Clear distinction of problems addressed

Future work should clearly define the specific problems being addressed, such as energy efficiency in wood packaging production and AI-based design iteration technology. Research should focus on reducing the number of cuts and engravings, which can significantly lower energy consumption in the packaging production process. Additionally, the importance of computational power and its energy consumption relative to other elements in the design process must be emphasized to ensure a holistic approach to sustainability.

Limitations

Data availability and quality

A significant limitation in applying CycleGANs and DL to product design is the need for large, high-quality datasets. The effectiveness of these models is heavily dependent on the availability of diverse and comprehensive data, which can be challenging to obtain, especially for niche or innovative products.

Computational resources

Training sophisticated DL models and CycleGANs requires significant computational resources, which can be a barrier for small design teams or individual designers. Future advancements in model efficiency and the democratization of computing power are essential to making these technologies more accessible.

Ethical Considerations and Design Responsibility

As artificial intelligence (AI) plays a more prominent role in the creative process, several important ethical considerations must be addressed. This includes ensuring that AI-generated designs do not inadvertently perpetuate biases or infringe upon intellectual property rights. Additionally, it is essential to maintain a human-centric approach to design, where AI enhances creativity rather than replaces it. Ethical design practices should prioritize inclusivity, fairness, and respect for intellectual property while leveraging AI's capabilities to innovate and improve design outcomes.

Promote and Share the Database

To maximize the impact and reach of the sustainability database developed in this research, several strategies for promotion and collaboration are recommended:

Outreach

Engage with educational institutions, design communities, and sustainability organizations to promote the database. This can be achieved through webinars, workshops, and presentations that highlight the benefits and functionalities of the database, encouraging widespread adoption and use.

Collaborations

Partner with designers and sustainability experts to expand and enrich the database's contents. Collaborative efforts can bring in diverse perspectives and expertise, enhancing the database's value and relevance. This includes inviting contributions from the design community, ensuring the database remains up-to-date and comprehensive.

CONCLUSIONS

1. The workflow in this research employs CycleGANs within a sustainable packaging design system for wood packaging engraving processes, which significantly assesses and improves the process to reduce packaging waste and optimize the design process.
2. This work adheres to a systematic design methodology divided into four main stages: a) user participatory design, b) assembly scheme design, c) detailed Finite Element Analysis (FEA) optimization, and d) computer numerical control (CNC) engraving

production. Sustainable packaging design has been a focal theme in recent research, necessitating assessments of environmental impacts and economic costs from the early conceptual design phase to maximize the recyclability value of products before the end of their lifecycle. Therefore, this workflow begins with the early design stages to optimize the environmental impact of conventional wood packaging. The workflow meets and enhances high user engagement and interactivity and allows for real-time updates of packaging patterns through cloud-based data iteration alongside a FEA optimization system that assesses the durability of the packaging. This approach supports both the practicality and aesthetic appeal of the packaging.

3. This research influences designers, consumers, and the industry's perception of packaging design, inspiring the creation of sustainable product packaging. The findings highlight the potential for advanced technologies to drive innovation in sustainable packaging. In the long term, the adoption of these methods may help minimize the negative environmental impacts of wood packaging, promoting more sustainable and efficient manufacturing practices within the industry.

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Article submitted: June 3, 2024; Peer review completed: June 30, 2024; Revisions received: July 20, 2024; Revisions accepted: July 26, 2024; Published: August 30, 2024.
DOI: 10.15376/biores.19.4.7824-7841