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RESEARCH PAPER

Advancing Ergonomic Cognition in Additive Manufacturing for Furniture Design: A Study of UTHM Students

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ABSTRACT
Industry 4.0 is transforming manufacturing skill requirements, emphasizing problem-based learning that integrates Human Factors and Ergonomics (HFE). This conceptual study introduces ergonomic cognition as a framework to understand how students perceive, respond to, and apply ergonomic principles in simulation-based learning. Guided by the Ontology of Techniques for Teaching, Learning, and Assessment (OTILIA), the study combines cognitive learning theories with ergonomic reasoning to explore student engagement in Design for Additive Manufacturing (DfAM), focusing on CO_2 laser cutting. A focus group of 21 final-year students from the Bachelor of Technology Management (Furniture Design and Manufacturing) program at Universiti Tun Hussein Onn Malaysia participated. Data were collected using the think-aloud method and analyzed through prescriptive coding based on studio themes. Descriptive statistics were used to track behavior across the three HFE domains: physical, cognitive, and organizational ergonomics. Findings reveal that integrating CO_2 laser cutting enhances ergonomic cognition-improving precision, customization, material efficiency, time management, and the learning curve during 3D miniature furniture production. The results support a triangular prescription framework linking ergonomic reasoning, interactive tools, and iterative design. Sustainability competencies were also embedded, prompting students to consider environmental impact, material use, and usability. This approach equips future designers to create eco-conscious, ergonomic, and industry-ready products aligned with sustainable smart manufacturing goals.

KEYWORDS: *Design for additive manufacturing; Ergonomic cognition; Industrial revolution 4.0; Simulation-based learning; Sustainability competencies.*

1. Introduction

Industrial Revolution 4.0 (IR 4.0) plays an important role based learning to help students understand modern industrial processes. Contextual learning, which focuses on hands-on experience, is more effective than traditional classroom methods [1]. However, achieving Malaysia's Sustainable Development Goals (SDGs), while adopting IR 4.0 technologies in education, present several challenges. One key challenge is ensuring sustainable practices in design education, especially in Design for Additive Manufacturing (DfAM) in the undergraduate program of a Malaysian public university [2, 3]. While DfAM helps students develop ergonomic cognition of HFE principles through furniture miniature, it also requires careful use of resources. The integration of CO_2 laser cutting in simulation-based learning must be managed (1) to reduce energy use and (2) material waste. Additionally, the increasing reliance on high-tech manufacturing processes must align with environmental sustainability efforts. To address these challenges, education programs should include sustainability-focused training, teaching students how to apply eco-friendly materials, energy-efficient methods, and waste reduction techniques [4, 5]. By combining technological innovation with sustainable practices, Malaysia can support both Industry 4.0 and its SDG goals, ensuring a skilled and environmentally responsible workforce.

Thus, the process of furniture making consists of a series of sequential stages that require careful

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analysis to ensure an ergonomically efficient workspace. This study aims to empirically address the number of stages involved in the furniture-making process and evaluate how these stages correspond to HFE principles within a structured furniture floor plan. It functions as a structured visual framework that maps key activities such as cutting, sanding, assembling, and finishing against HFE principles, including physical layout, worker posture, material flow, and tool accessibility. The furniture floor plan serves as both a planning and evaluation tool to ensure that each stage of the manufacturing process aligns with ergonomic standards, minimizes strain, and enhances task performance within a cohesive workspace. However, three will be reflected three research questions according to (1) what kind of framework model by identifying key themes related to workflow efficiency? Which means (2) what is the task required for DfAM? Hence, this study employs a think-aloud methodology, wherein (3) what are students verbalize their cognitive processes as they are related to HFE principles while engaging in the workflow.

2. Literature Review

Design education is evolving with the integration of DfAM, combining traditional and digital fabrication methods while emphasizing ergonomic workspace design. This approach enhances students' ability to create functional, user-centered designs through hands-on, practice-driven learning.

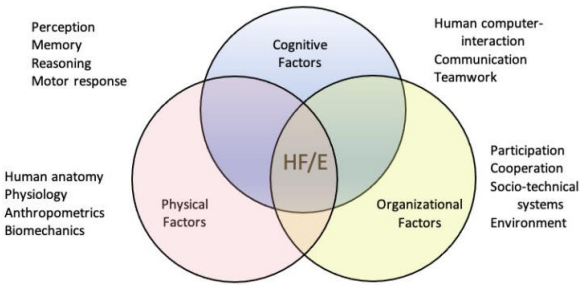


Fig.1. The integration of human factors and ergonomic principles–the Venn diagram

In Figure 1, the integration of HFE into design education, particularly through DfAM which supports the development of ergonomic awareness and user-centered thinking in students. The Venn diagram illustrates three interrelated HFE domains: Cognitive, Physical, and Organizational factors. Cognitive factors involve perception, memory, and decision-making during design modeling and iterative tasks. Physical factors relate to body posture, anthropometrics, and biomechanical interaction with tools such as CO_2 laser cutters. Organizational factors focus on teamwork, communication, and environmental setup within the studio-based learning. DfAM encourages hands-on, experiential learning where students plan workflows, optimize ergonomic layouts, and engage in collaborative tasks. The intersection of all three domains-ergonomic cognition-enhances students' capacity to balance creativity with functional usability. This framework not only reinforces real-time design precision and efficiency but also prepares students for sustainable and human-centered manufacturing aligned with Industry 4.0 standards. Small-scale DfAM learning allows students to explore 3D printing, laser cutting, and digital modeling to develop and refine designs efficiently. By working with miniature prototypes, they can assess structural feasibility, material use, and ergonomic factors in a cost-effective and iterative process [5-8].

This method encourages creativity while reinforcing real-world manufacturing constraints [8, 9]. The integration of traditional and digital methods bridges the gap between handcrafted techniques and precision-based fabrication. While traditional prototyping helps students understand material properties and design aesthetics, digital tools like CO_2 laser cutting and parametric modeling introduce accuracy and efficiency. Combining these approaches provides a balanced learning experience, preparing students for diverse design challenges [10]. By ergonomic cognition, the ergonomic workspace design is crucial for ensuring efficiency, comfort, and usability in both educational and professional settings. Referring to the macro-ergonomic factors, such as workspace layout and tool placement, influence workflow, while micro-ergonomic considerations, like component usability and human interaction, ensure functional design outcomes. Using scaled prototypes and cognitive assessments, how users interact with their designs, improving usability and accessibility. By integrating DfAM, traditional and digital methods, and ergonomic design, students gain practical experience, problem-solving skills, and a deep understanding of user needs. This holistic approach prepares them to create functional, efficient, and human-centered designs in modern manufacturing and design industries.

2.1. Small-scale DfAM learning for HFE principles in design education perspectives

DfAM has gained significant attention in design education due to its ability to enhance students' understanding of digital fabrication, ergonomic design, and production efficiency. In a small-scale learning environment, DfAM principles are applied within structured educational settings to facilitate hands-on learning and experimentation. This approach enables students to explore both macro-ergonomic and micro-ergonomic considerations in the design and fabrication of products, fostering a deeper comprehension of human-centered design and workflow optimization [9, 10]. The integration of HFE principles within small-scale DfAM learning ensures that students not only focus on the technical aspects of 3D printing but also develop an awareness of spatial design, user comfort, and functionality in real-world applications [11].

Macro-ergonomics in small-scale DfAM learning refers to the overall organization of the fabrication space, ensuring an efficient and logical arrangement of workstations, 3D printers, and storage areas to support smooth workflow processes. As highlighted by Hendrick and Kleiner (2002), macro-ergonomic considerations are essential in optimizing work-space layouts to enhance productivity and reduce unnecessary physical strain. Within an educational context, this involves designing lab or workshop layouts that allow students to easily transition between ideation, prototyping, and evaluation stages. An effective spatial arrangement can significantly impact students' learning experiences, ensuring that they can navigate their work environment efficiently while focusing on iterative design processes [8, 12, 13].

On the other hand, micro-ergonomics in small-scale DfAM learning focuses on the design of individual components and workstations to ensure optimal interaction between the user and the tools or products being created. Micro-ergonomic considerations involve aspects such as tool accessibility, working height, grip comfort, and the overall usability of 3D-printed components [12]. By emphasizing micro-ergonomic principles, students can refine their product designs to align with human factors, improving usability and reducing the risk of musculoskeletal discomfort [15]. Furthermore, additive manufacturing allows for rapid prototyping, enabling students to test, modify, and optimize their designs based on ergonomic feedback, an essential skill in modern design practices [16, 17].

2.2. Integration of traditional and digital methods derives key themes of HFE principles

The comparison between traditional and simulation-based methods in miniature furniture model making reveals significant differences in ergonomic cognition and learning efficiency. Traditional methods, which rely on manual craftsmanship, often result in higher variability in model dimensions due to human error, whereas simulation-based approaches utilizing CAD software and additive manufacturing ensure greater precision and consistency [17, 18]. Moreover, traditional methods impose a higher cognitive load on students as they must rely on spatial awareness and trial-and-error problem-solving, while simulation-based techniques reduce cognitive fatigue by allowing real-time visualization and modifications before physical production.

Ergonomic understanding is also enhanced in the simulation-based approach, as digital models enable rapid adjustments and iterative testing without the material constraints faced in traditional crafting. In terms of production efficiency, traditional methods require longer fabrication times due to manual cutting and assembly, whereas digital fabrication through laser cutting and 3D printing accelerates the process. Furthermore, material waste is notably higher in traditional methods due to cutting errors and physical prototyping, while simulation-based techniques promote sustainability by minimizing waste through precise digital fabrication. Another critical aspect is customization, where traditional methods limit the complexity of ergonomic designs, whereas digital tools allow for intricate, user-specific adaptations. Additionally, user experience and feedback integration are more effective in simulation-based learning, as students can conduct digital ergonomic analyses before producing physical models, reducing the need for costly and time-consuming modifications [17, 18]. Based on these findings, data analysis is expected to demonstrate that simulation-based methods significantly enhance ergonomic cognition by improving efficiency, accuracy, and iterative testing. However, traditional approaches still offer valuable hands-on learning experiences, suggesting that a hybrid approach integrating both methods may provide the most comprehensive

educational outcome in design learning.

2.3. Design for ergonomic workspaces

The design of a workspace significantly influences the efficiency, comfort, and productivity of workers, particularly in hands-on disciplines such as furniture making. An ergonomically optimized furniture floor plan ensures that workers can move seamlessly between different stages of production while minimizing physical strain and enhancing workflow efficiency [19]. The spatial organization of a furniture-making workshop must accommodate both human movement and the necessary equipment, ensuring that all production stages are arranged logically to reduce unnecessary exertion and fatigue. Studies on ergonomic workspace design emphasize the importance of factors such as workstation arrangement, tool accessibility, and movement pathways in optimizing task efficiency [20].

In the context of a furniture-making process, a well-optimized furniture floor plan follows the sequential stages of production, from material preparation to assembly and finishing. Empirical studies suggest that inefficient spatial layouts can lead to increased task completion time, unnecessary worker fatigue, and reduced overall productivity [18, 21]. By analyzing the workflow through empirical observation and ergonomic evaluation, researchers can identify key areas where workspace modifications can improve movement efficiency and task completion rates.

Furthermore, cognitive ergonomics plays a crucial role in furniture floor plan design, as workers' ability to navigate the space with minimal cognitive load enhances both safety and efficiency [22].

3. Methodology

First, this methodology provides valuable qualitative insights into how students perceive and interact with their working environment ontologically, highlighting potential areas for improvement in workspace organization from psychomotor taxonomy levels [23]. Then, the descriptive study gauges the attributes' categories aligning with the key themes of activity sequences. By integrating empirical data with user cognition, the findings of this study will contribute to the development of optimized furniture floor plans for the key themes of ergonomics cognition that enhance both productivity and ergonomic well-being in furniture-making workspaces.

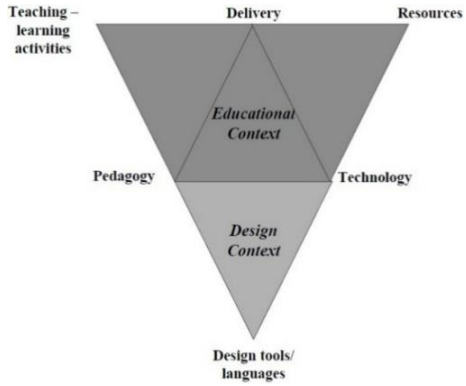


Fig.2. The main principles in the design of teaching-learning activities

Second, in the design context introduces an ontology of techniques for teaching, learning, and assessment purposes (OTILIA) by the expert D. Mota et al., (2014), it focusing on the design of teaching-learning activities in design education relies on key principles that help students develop skills and apply knowledge effectively according to the bottom triangulation of pedagogy-technology-design tools as Figure 2. Six pedagogical principles are addressed, namely (1) active learning, (2) experiential learning, (3) scaffolded learning, (4) reflective practice, and (5) collaborative learning; support hands-on learning and skill development, aligning with psychomotor taxonomy levels following;

- Active learning encourages direct engagement with design tasks rather than passive learning.
- Experiential learning builds on this by emphasizing real-world practice.
- Scaffolded learning provides structured support as students progress.
- Reflective practice helps students evaluate their work and improve their designs.
- Collaborative learning encourages teamwork and knowledge sharing.

Third, as identified above, the above principles create an effective learning framework in design education. By incorporating active, experiential, scaffolded, reflective, and collaborative learning, educators help students develop both foundational and advanced design skills, preparing them for real-world challenges [23, 24].

Therefore, an effective use of the OTILIA model, referring to the integration of CO_2 laser cutting in Design for Additive Manufacturing (DfAM), requires a structured pedagogical approach that ensures students develop essential skills in digital fabrication and ergonomic design. Hence, the

research of a case study impacts to emphasize the OTILIA model that it's provides a triangulated framework that enhances simulation-based learning, cognitive decision-making, and psychomotor skill development. The model procedures were incorporating the teaching-learning techniques, knowledge, and initially summarizing,

- Observation and Theory (O)–Students first gain foundational knowledge about laser cutting technology, material properties, and DfAM principles. This phase includes theoretical instruction, case studies, and industry insights to build a conceptual understanding of digital fabrication.
- Technical Application (T); Learners engage in hands-on laser cutting exercises to understand machine operations, software interfaces, and design constraints. This stage emphasizes precision, safety, and workflow optimization in digital fabrication.
- Iterative Design (I); Through an iterative process, students refine their design models based on feedback, material performance, and ergonomic usability. Experimentation and prototyping allow learners to assess structural integrity and manufacturability.
- Logical Integration (L); This phase connects laser-cutting techniques with ergonomic and cognitive evaluations. Students analyze how

fabrication constraints impact usability and functionality, integrating knowledge from case studies and empirical research.

- Innovation and Experimentation (I); Encouraging creativity, students explore advanced laser-cutting applications, such as parametric design and hybrid fabrication techniques. This stage fosters critical thinking and problem-solving.
- Assessment and Reflection (A); The final phase involves usability testing, peer reviews, and self-reflection on design efficiency, material consumption, and user-centered design considerations. This process reinforces learning outcomes and prepares students for real-world applications.

On the other hand, the role of students' comprehensive learning will be projected and articulated in the flow of simulation-based learning holistically as Figure 3. The evolution of design education has been significantly influenced by the integration of DfAM, digital fabrication, and ergonomic considerations. A structured simulation-based learning methodology enhances students' understanding of ergonomic usability, cognitive decision-making, and psychomotor skill development. Fourth, this study employs a comprehensive research framework that integrates design studio activities, empirical case studies, cognitive evaluation, and usability testing to assess the impact of traditional and digital fabrication methods on ergonomic workspace design. A structured simulation-based learning methodology plays a critical role in enhancing students' understanding of ergonomic usability, cognitive decision-making, and psychomotor skill development by providing an interactive and experiential learning environment.

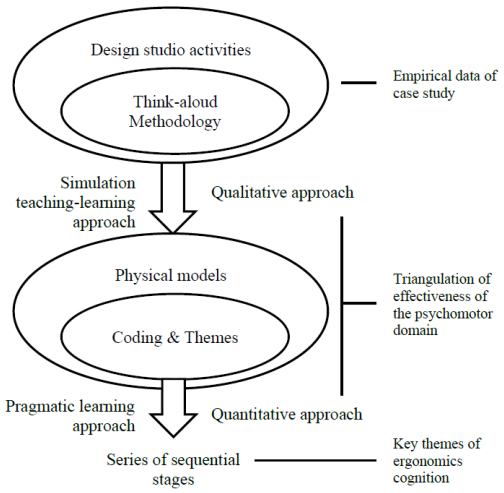


Fig.3. A flow of methodology framework for simulation-based learning

In another teaching-learning perspective, research in pragmatic learning approaches supports this claim by emphasizing the importance of hands-on engagement, iterative problem-solving, and real-time feedback in skill acquisition and cognitive development. From the previous study, a pragmatic research perspective, Kolb's Experiential Learning Theory (ELT) underscores that students learn best when they can actively experience, reflect, conceptualize, and apply knowledge in real-world contexts. This aligns with simulation-based learning, where students engage in realistic design challenges, ergonomic assessments, and prototyping exercises that enhance spatial reasoning, hand-eye coordination, and material adaptability [24]. Similarly, constructivist theories argue that learning-by-doing fosters deep cognitive processing, improving decision-making skills in ergonomic design applications.

Tab.1. Observation method study between manual skill and digital precision in design studio activities

Key themes	Attributes	Traditional method	Additive manufacturing method
1. Design Process	3D Miniature method (3DMM)	Hand-drawn sketches, physical prototyping, and manual adjustments	Digital modeling, CAD software, and iterative 3D printing
2. Prototyping		Handmade using wood, foam, or clay	Layer-by-layer/sheet printing using plain materials like board
3. Precision	3D Furniture assemble (3DFA)	Limited by manual tools and craftsmanship	High precision due to digital accuracy and automation
4. Customization		Time-consuming and requires skilled labor	Easily customizable with parametric designs
5. Material Waste		Higher due to cutting and shaping	Minimal waste as material is added precisely
6. Time Efficiency	3D Miniature representation (3DMR)	Longer due to manual crafting and modifications	Faster production with digital adjustments
7. Learning Curve		Hands-on skills, craftsmanship, and manual techniques	Digital design skills, software proficiency, and printing knowledge
8. Cost	3D Miniature quality (3DMQ)	Material costs depend on availability and waste	Initial setup for 3D printing may be expensive but cost-effective long-term
9. Ergonomics and Innovation		Limited by manual prototyping capabilities	Allows for ergonomic testing and innovative geometries

Furthermore, studies in human factors and ergonomicseducation highlight that virtual simulations and 3D modeling environments provide students with a risk-free space to explore design iterations, material interactions, and anthropometric considerations before physical production [4, 10, 18, 25, 26]. This reduces design errors, enhances customization capabilities, and sharpens students' ability to predict user comfort and functionality as well as key aspects of ergonomic usability.

3.1. Evaluation of ergonomic usability testing from the verbalization of the think-aloud methodology

Traditional methods rely on craftsmanship and manual skill, whereas additive manufacturing emphasizes digital precision, customization, and efficiency, as evidenced by the design studio activities. By the observation approach, integrating both approaches can provide a comprehensive learning experience for students in defining the attributes labeling as Table 1. Evidently, the evaluation of ergonomic usability plays a crucial role in assessing how well a design or product supports user interaction, comfort, and efficiency. In the context of design education and digital fabrication, ergonomic usability testing ensures that products such as furniture, workspaces, and interactive objects align with human factors and ergonomic principles. This verbalization of think-aloud methodology provides an in-depth analysis of ergonomic usability testing, structured into key sub-topics that enhance the evaluation framework. Based on the essential OTILIA model method under the Assessment and Reflection of final stage procedure, the study used a qualitative exploratory approach within a design studio environment to explore how ergonomic usability is addressed during digital fabrication (experimentation). The participants were final-year design students working with tools such as CO_2 laser cutters and CAD software. Data collection involved think-aloud protocols, observation field notes, and ergonomic usability rubrics. The analysis combined thematic coding and heuristic evaluation, using ergonomic criteria and established usability principles to interpret students' design reasoning and interaction with tools. During the heuristic rubric assessment, a scoring scale (e.g., 1= Poor, 2= Fair, 3= Good, 4= Very Good, 5= Excellent) was applied to evaluate aspects such as (1) posture support–52.38%: Very Good, (2) reachability–47.62%: Excellent, (3) ease of interaction–52.38%: Excellent, (4) user comfort–42.86%: Very Good

and (5) task efficiency–52. Supporting tools included ergonomic checklists, audio/video recorders, and digital fabrication equipment to capture and assess the design process effectively.

3.2. Statistical test examines the attributes of ergonomic usability

The assessment of normality is a fundamental prerequisite in statistical analysis, as it determines the appropriate selection of parametric or non-parametric tests by the Statistical Package for the Social Sciences (SPSS). In this study, two widely recognized normality tests were conducted: the Kolmogorov-Smirnov Test and the Shapiro-Wilk Test. The results, as presented in the table, indicate that the Shapiro-Wilk Test is more appropriate for small sample sizes ($n< 50$) while remaining effective for larger datasets of up to 2000 observations [27, 28]. Given that the sample size in this study consists of 21 observations for each variable, the Shapiro-Wilk Test is deemed the most suitable choice for evaluating data normality.

In Table 2, the results of the Shapiro-Wilk Test indicate that all variables: (1) 3D Miniature Method; 3DMM, (2) 3D Furniture Assemble; 3DFA, (3) 3D Miniature Representation; 3DMR, and (4) 3D Miniature Quality; 3DMQ-demonstrated statistically significant deviations from normality ($p< .05$). This suggests that the dataset does not follow a normal distribution, warranting the use of non-parametric statistical methods in subsequent analyses.

The findings reinforce the necessity of employing robust statistical techniques that do not assume normality, such as the Spearman's rho correlation test, which is more appropriate for ordinal or non-normally distributed data. By systematically assessing the distribution of the dataset using the Shapiro-Wilk Test, this study ensures methodological rigor in data analysis [28].

Next, the results of the Spearman's rho correlation analysis indicate a strong positive relationship between 3D Furniture Assembly, 3DFA, and 3D Miniature Representation; 3DMR ($r= 0.802$, $p< 0.01$, $n= 21$) as Table 3. This statistically significant correlation suggests that improvements in 3D Miniature Representation are closely associated with enhanced efficiency and accuracy in furniture assembly.

This finding highlights the importance of detailed and precise miniature models in the assembly process, as well-developed representations may aid in better visualization, reduced assembly errors, and improved structural alignment.

Tab.2. Tests of normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
3D Miniature method (3DMM)	.348	21	.000	.640	21	.000
3D Furniture assemble (3DFA)	.323	21	.000	.750	21	.000
3D Miniature representation (3DMR)	.296	21	.000	.774	21	.000
3D Miniature quality (3DMQ)	.310	21	.000	.811	21	.001
a. Lilliefors significance correction						

Tab.3. Spearman's Rho correlations

		3DMM	3DMQ	3DMR	3DFA
3DMM	Correlation coefficient	1.000	-.173	-.267	-.424
	Sig. (2-tailed)	.	.455	.242	.055
	N	21	21	21	21
3DMQ	Correlation coefficient	-.173	1.000	.554**	.450*
	Sig. (2-tailed)	.455	.	.009	.041
	N	21	21	21	21
3DMR	Correlation coefficient	-.267	.554**	1.000	.802**
	Sig. (2-tailed)	.242	.009	.	.000
	N	21	21	21	21
3DFA	Correlation coefficient	-.424	.450*	.802**	1.000
	Sig. (2-tailed)	.055	.041	.000	.
	N	21	21	21	21
**. Correlation is significant at the 0.01 level (2-tailed).					
*. Correlation is significant at the 0.05 level (2-tailed).					

The strong correlation supports the notion that accurate 3D miniature models can serve as effective references in guiding users through the furniture assembly process, ultimately enhancing workflow efficiency. Therefore, the suggestion of future research should explore the cognitive link between 3DFA and 3DMR within spatial cognition theories, focusing on mental rotation, visual-spatial intelligence, and factors influencing skill development.

4. Result and Discussion

In this section, the research study is consistently uses the significant finding of Spearman's rho correlation analysis refers a strong positive relationship between 3D Furniture Assembly, 3DFA, and 3D Miniature Representation, 3DMR, as earlier findings previously. Based on the methodology results, the research study use the triangulation of data analysis which is consisted and divided by two methods namely (1) verbalization and (2) mapping strategy method via design context learning.

First, the verbalization of think-aloud methodology refers to students verbalize their cognitive processes related to ergonomics while engaging in the workflow. There will be generated and produced the design manuscript into the design specimens accordingly. In a qualitative design study, a design manuscript refers to the visual and conceptual documentation developed by participants (such as design students or practitioners) that captures their design thinking, decision-making processes, and form development over time. It includes sketches, diagrams, annotated drawings, digital models, and iterative design outputs that reflect the cognitive and ergonomic considerations embedded throughout the design process. The design manuscript serves both as a research artifact and a traceable narrative, supporting qualitative analysis by revealing how ideas evolve into tangible design specimens through reflective and heuristic reasoning.

Second, the mapping strategy method displays the tabulation analysis of future research should explore how further refinements in 3D representation techniques can optimize assembly efficiency and user experience digital fabrication and ergonomic design applications. In this qualitative study, a mapping strategy manuscript is employed as a visual-analytical tool to organize and interpret relationships among key variables in digital fabrication, such as 3D representation techniques, ergonomic criteria, user experience, and assembly efficiency. This strategy aids in synthesizing insights derived from observational data, think-aloud protocols, heuristic evaluations, and design iterations, enabling a deeper understanding of how design decisions evolve within the fabrication workflow. The mapping process supports tabulated and diagrammatic representations, making it effective for identifying emerging themes and guiding future research directions. Inclusion criteria for the mapping strategy manuscript consist of relevant qualitative data such as user interaction patterns, ergonomic rubric scores, 3D design developments, and feedback drawn from usability testing. These components are visually or narratively mapped to trace design reasoning and performance alignment. Conversely, exclusion criteria eliminate non-contextual raw data, unprocessed numerical metrics, and abstract
ideas lacking empirical grounding in the observed design activity. The mapping strategy manuscript ultimately serves as both a reflective and projective framework for enhancing the understanding of ergonomic integration in digitally fabricated outputs.

Finally, by validating a meaningful association between these two variables, this study reinforces the role of high-quality 3D modeling in design education and additive manufacturing practices. As statistical testing resulted, the key themes of workflow for 3D Furniture Assembly namely (1) Precision, (2) Customization, (3) Material Waste and 3D Miniature Representation: (4) Time Efficiency, (5) Learning Curve will be tabulated in further discussion. The association of descriptive statistics refers to linking observed design themes with basic numerical summaries like frequencies or rankings. This helps highlight patterns such as precision, customization, or time efficiency in 3D furniture assembly. It supports deeper understanding by combining thematic insights with measurable trends, reinforcing the value of 3D modeling in design education and fabrication.

4.1. Design specimens of a physical model for the prescriptive analysis

Design activity plays a crucial role in the development of physical models, where the choice of methodology significantly impacts accuracy, efficiency, and overall quality. In Figure 4, this study examines the prescriptive aspects of design activity by comparing two distinct design

methods namely (1) traditional and (2) digital-using the think-aloud methodology within a simulation-based learning framework.

The findings highlight the strengths and limitations of each approach, providing structured guidance for optimizing design processes for students.

- Systematic Approach to Design Specimen Creation; This study provides a structured way to compare traditional and digital design methods. By following a clear process, students can create physical models more consistently and accurately. A controlled evaluation helps in choosing the right method to improve precision and reduce errors.
- Accuracy in Material Handling and Cutout Precision; Improving accuracy in cutting and assembling materials is essential. The study found that the traditional method resulted in improper cutouts, showing inefficiencies in manual techniques. To improve quality, traditional methods need refining, or precision tools should be used. The digital method, on the other hand, created proper cutouts, proving its accuracy and highlighting the benefits of digital fabrication for students.
- Adoption of Digital Methods for Enhanced Design Accuracy; The study recommends using digital methods to improve precision and efficiency. Digital techniques create more accurate cutouts, reduce material waste, and minimize errors. Using tools like computer-aided design (CAD) and digital fabrication can streamline the design process and enhance the quality of physical models for students.
- Structured Cognitive Evaluation through Think-aloud Methodology; The think-aloud methodology helps analyze how students approach different methods. By speaking their thoughts aloud, students reveal their decision-making process, challenges, and problem-solving strategies. This approach should be used in future design research to better understand cognitive aspects of students' design activities.

The prescriptive analysis of design activity in this study directs future design practices toward adopting digital methodologies for improved accuracy, enhancing traditional techniques to reduce errors, and implementing structured evaluation methods to assess students' design decision-making.

The findings emphasize the importance of precision in material handling, advocate for the integration of digital fabrication tools, and reinforce the value of think-aloud methodologies in design research. These prescriptive insights contribute to the ongoing development of best practices in design specimen creation, ensuring greater efficiency and effectiveness in students' physical model development.

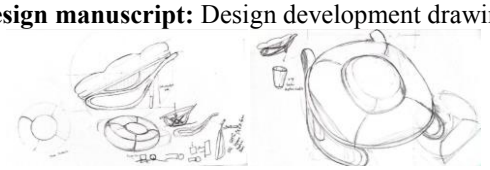
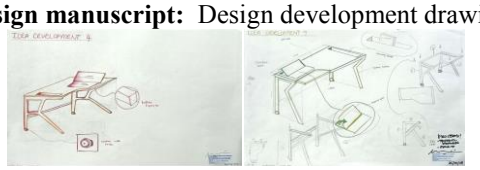
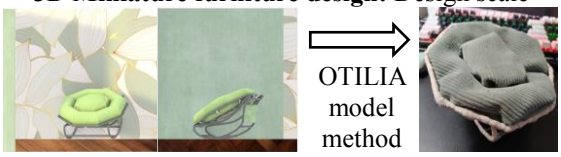
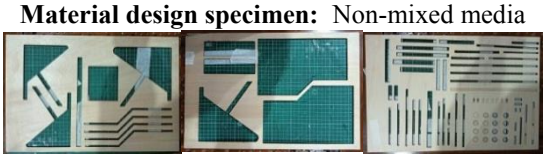
Traditional method	**Digital method**
Design concept: Modern rocking chair	**Design concept:** The modular concept of study table.
Design manuscript: Design development drawing  *Ideation*	**Design manuscript:** Design development drawing  *Ideation*
3D Miniature furniture design: Design scale  OTILIA model method *3D Modeling* *3D Miniature*	**3D Miniature furniture design:** Design scaling OTILIA model method *3D Modeling* *3D Miniature*
Material design specimen: Mixed media -Not available- *Improper cut out of design layout*	**Material design specimen:** Non-mixed media  *Proper cut out of design layout*

Fig.4. Comparison of two design methods by think-aloud methodology approaches the simulation-based learning

Tab.4. Tabulation analysis for an impact and effect based on ergonomics cognition by the prescription of design studio activities

Attribute	Key themes of 3D modeling	Impact on design education and additive manufacturing	Ergonomics cognition detailing for students	Effect on sequential stages of additive manufacturing for ergonomics cognition
3DFA	3. Precision	Ensures accurate fitting and alignment of components, reducing errors	Enhances students' understanding of human-centered design and fit accuracy	Pre-Processing and Digital Design Optimization
	4. Customization	Allows for tailored designs, adapting to specific user needs	Encourages creative problem-solving in ergonomic furniture and user comfort	Material Selection and Parametric Modeling
	5. Material waste	Optimizes material usage, minimizing excess and costs	Teaches sustainable design principles and resource-efficient manufacturing	Printing and Layer Deposition
3DMR	6. Time efficiency	Speeds up prototyping and evaluation, reducing production time	Helps students iterate and test ergonomic concepts quickly	Post-Processing and Refinement
	7. Learning curve	Enhances user adaptability, making design processes more intuitive	Strengthens students' spatial visualization and ergonomic assessment skills	Feedback and Iterative Design

4.2. Ergonomics cognition by the integration of CO_2 laser cutting in simulation-based learning

In Table 4, the comprehensive table bridges 3D modeling, ergonomics cognition, and additive manufacturing, showing how sequential stages refine precision, customization, sustainability, efficiency, and learning adaptability in design education and manufacturing.

The integration of DfAM processes with ergonomics cognition enhances design education by ensuring precision, customization, material efficiency, time management, and adaptability. The pre-processing and digital design optimization phase refines high-resolution models, ensuring ergonomic accuracy before fabrication. Material selection and parametric modeling allow for adaptive choices that enhance comfort and usability, ensuring designs meet human-centered needs. During printing and layer deposition, optimized slicing techniques minimize material waste while maintaining structural integrity. The post-processing and refinement stage focuses on surface finishing, support removal, and assembly testing, improving usability and ergonomic effectiveness. Finally, the feedback and iterative design phase enables students to analyze and refine their models based on real-world usability, fostering continuous improvement. By following these sequential AM stages, students develop essential skills in ergonomically sound, resource-efficient, and user-focused design, bridging digital modeling with real-world applications.

4.3. Knowledge gap of pragmatic research for advanced ergonomics cognition

In Figure 4, the triangular prescription of design context presents a structured and progressive model for enhancing ergonomic design education through simulation-based learning. Beginning with 2D drawing and 3D representation, students are introduced to core visual communication and spatial reasoning skills. These activities help learners conceptualize ergonomic forms and user-centered solutions, fostering the cognitive development required to understand the relationship between human factors and design outcomes. This phase builds visual literacy, ergonomic awareness, and design sensitivity-essential elements in developing advanced ergonomics cognition.

The middle tier of the triangle involves exporting files and navigating design platforms such as Adobe Illustrator, AutoCAD, SolidWorks or 3D Rhino. This stage promotes technical fluency

by guiding students through digital workflows, file conversion, and preparation for fabrication. Converting design concepts into AI or CAD files requires analytical thinking and introduces students to the affordances and constraints of digital tools. These experiences align closely with the practical demands of additive manufacturing and digital prototyping, enabling students to apply ergonomic principles in real-world design contexts. At the base of the model, the process culminates in physical realization through CO_2 laser cutting and engraving. This phase allows students to transform digital designs into physical prototypes, reinforcing psychomotor skills and supporting iterative, reflective practice. Simulation-based learning provides immediate feedback, encouraging experimentation and refinement. However, a persistent knowledge gap remains in pragmatic research exploring how structured, tool-integrated learning environments shape advanced ergonomics cognition. Implementing this triangular model in design education helps bridge this gap by demonstrating how experiential, simulation-driven instruction enhances cognitive development, ergonomic reasoning, and innovation in human-centered design.

5. Conclusion

The study addresses the research questions answered that CO_2 laser cutting in simulation-based learning enhances ergonomics cognition by improving precision, customization, material waste, time efficiency, and learning curve as key themes of 3D modeling. Second, this hands-on approach allows students to develop practical problem-solving abilities, reinforcing the importance of digital fabrication in design education. By engaging with laser-cut prototypes, students gain a deeper understanding of ergonomic usability, material behavior, and human-centered design principles, while also learning to optimize material use and minimize waste, supporting sustainable design practices. Third, a triangular prescription of design context as a framework model aligned with pragmatic design studio methodologies, which emphasize the tasks of DfAM learning through real-world application and iterative problem-solving as well as Simulation-Based DfAM Learning. Coincidentally, research in experiential learning theories, such as Kolb's Learning Cycle, supports the idea that students learn best through action, reflection, and refinement. By integrating CO_2 laser cutting with structured studio activities, students gain practical skills that bridge theoretical knowledge with real-world application. Also, there will be fostered innovation, sustainability, and continuous improvement in ergonomic design.

Future research should investigate and gauge how digital fabrication tools, such as CO_2 laser cutters and 3D modeling software that enhance sustainable design thinking and inform the development of a conceptual framework titled "Ergonomic Cognition in Simulation-Based DfAM Learning". This framework integrates HFE domains-cognitive, physical, and organizational with simulation-based fabrication processes. It maps interactions between ergonomic reasoning, iterative design, tool handling, and sustainability awareness. Serving as both a pedagogical and evaluative model, the framework supports curriculum development, fosters Industry 4.0 readiness, and promotes innovation in design education through hands-on, ergonomically informed learning.

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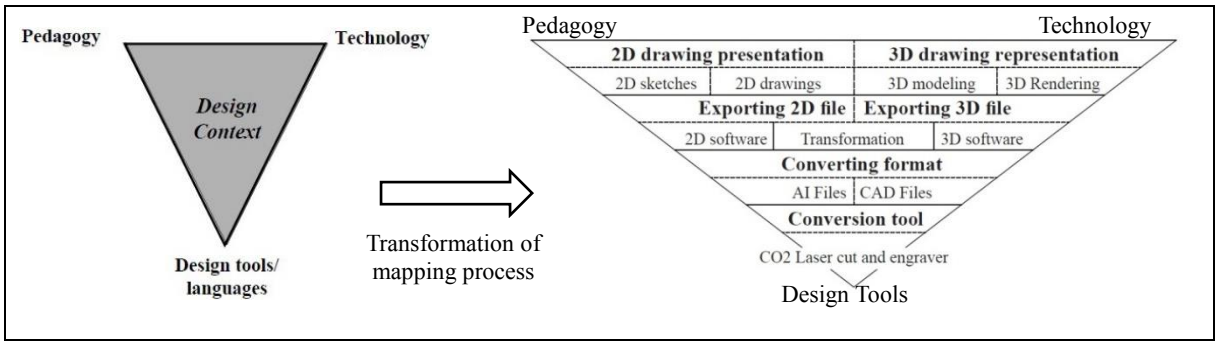

Fig.5. A triangular prescription of design context for the teaching-learning techniques knowledge

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