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Integration of digital manufacturing tools in the development of ergonomic didactic resources: a case study in preschool education

Integración de herramientas de manufactura digital en el desarrollo de recursos didácticos ergonómicos: caso de estudio en educación preescolar

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ABSTRACT

This study addressed the need to improve the ergonomic conditions of school furniture in early childhood education, considering its impact on children's posture, safety, and concentration. The objective was to design, manufacture, and validate an ergonomic educational module (desk and chair) for students aged 3 to 5, using digital manufacturing tools. An experimental approach was applied across five phases: collection of anthropometric data, CAD modeling, computer-aided manufacturing (CAM), technical assembly, and structural, ergonomic, and pedagogical validation. The design adhered to international standards (ISO 5970, UNE-EN 1729-2, ISO 7174-1) and guidelines from the Peruvian Ministry of Education (MINEDU). Results showed 92% material utilization efficiency, average production time of 85 minutes, and high structural resistance. Validation with teachers and children demonstrated 94% postural adequacy and high satisfaction levels regarding ergonomics, safety, and functionality. It was concluded that integrating digital manufacturing technologies into the development of ergonomic school furniture is feasible and offers potential for replication and transfer to public early childhood education institutions.

Keywords: child learning, CAD design, school ergonomics, computer-aided manufacturing, pedagogical validation

RESUMEN

Este estudio abordó la necesidad de mejorar las condiciones ergonómicas del mobiliario escolar en la educación inicial, considerando su impacto en la postura, seguridad y concentración de los niños. El objetivo fue diseñar, fabricar y validar un módulo educativo ergonómico (mesa y silla) para estudiantes de 3 a 5 años, utilizando herramientas de manufactura digital. Se aplicó un enfoque experimental con cinco fases: recolección de datos antropométricos, modelado CAD, manufactura asistida por computadora (CAM), ensamblaje técnico y validación estructural, ergonómica y pedagógica. El diseño consideró normativas internacionales (ISO 5970, UNE-EN 1729-2, ISO 7174-1) y lineamientos del MINEDU. Los resultados mostraron una eficiencia de corte del 92 %, tiempos de fabricación promedio de 85 minutos y alta resistencia estructural. La validación con docentes y niños evidenció un 94 % de adecuación postural y niveles altos de satisfacción en ergonomía, seguridad y funcionalidad. Se concluyó que es viable integrar tecnologías de fabricación digital en el desarrollo de mobiliario escolar ergonómico, con potencial de replicabilidad y transferencia a instituciones públicas de educación inicial.

Palabras clave: aprendizaje infantil, diseño CAD, ergonomía escolar, fabricación asistida computadora, validación pedagógica

1. INTRODUCTION

Early childhood education constitutes a critical stage in the integral formation of the human being, as it consolidates fundamental cognitive, motor, and socio-emotional skills (Rafiyya et al., 2024). At this level, the physical classroom environment, and particularly the school furniture, plays a determining role in learning quality, as it directly influences children's posture, concentration, and comfort during pedagogical activities (Baba et al., 2024; Chen & Tsai, 2024). The adaptation of these resources to anthropometric and functional criteria has led to the conceptualization of so-called ergonomic didactic resources, understood as physical devices designed to ensure safety, stimulation, and pedagogical accessibility according to child development (Esenarro et al., 2023; Gumasing et al., 2023).

In parallel, technological advances have transformed traditional design and production methods, enabling a transition towards digital manufacturing models (Kraus et al., 2021; Yan & Wang, 2024). This change has been driven by the availability of CAD/CAM software (Budi & Sukmono, 2023), computer numerical control (CNC) machines (Yao et al., 2024), laser cutters, and 3D printers, whose capabilities allow for the development of customized products with high precision, shorter production times, and optimized costs (Rasu, 2023). In the educational field, this evolution represents a strategic opportunity to innovate not only in content and methodologies but also in the material means that support the teaching-learning process. At the university level, these technologies have begun to be implemented in design laboratories and training workshops, promoting applied technical competencies and project-based thinking with social impact (Kantaros et al., 2022; Tofail et al., 2018).

From a theoretical perspective, this research is based on Schumpeter's theory of innovation, which views technological change as a driver of structural development, and on general systems theory, which allows for understanding the educational ecosystem as an interdependent network of technical, human, and pedagogical factors (Montoya, 2004; Martínez & Chávez, 2024). In practice, however, considerable challenges persist: many educational institutions still use standardized school furniture that does not meet ergonomic criteria nor adapts to the real conditions of child users (Cardon et al., 2004; Podrekar Loredan et al., 2022). Added to this is the weak articulation between technological capabilities developed at universities and their effective transfer to school environments.

At the research level, a growing volume of studies has been identified on the use of digital manufacturing tools in education, particularly in the design and prototyping of didactic furniture (Kalita et al., 2019; Soomro et al., 2021; Tihinen et al., 2021). However, most focus exclusively on the technical phase of the process (modeling, materials, assembly), without addressing the pedagogical, ergonomic, or contextual validation in an integrated manner. Additionally, the most developed works are often oriented towards urban contexts or those with high technology access, limiting their applicability in rural or resource-constrained environments. This gap highlights the need for proposals that systematically integrate the phases of design, manufacturing, technical validation, and educational evaluation of the generated products (Cash et al., 2023; Fazeli & Peng, 2022).

In response to this scenario, the present study proposes the development and validation of an ergonomic, detachable educational module (table and chair) for students aged 3 to 5 years, using digital manufacturing tools available in university laboratories. Unlike previous approaches, this research documents all stages of the process: from problem identification and digital design to assisted manufacturing, structural assembly, mechanical testing, and pedagogical validation in context. Additionally, standards from the Ministry of Education of Peru (MINEDU, 2023) are applied to ensure regulatory compliance of the prototype.

The research follows an applied design with a mixed approach, aimed at generating a replicable product with low cost and high technical precision. As its main contribution, it seeks to demonstrate that it is possible to integrate digital manufacturing technologies in the development of ergonomic educational materials, promoting both pedagogical innovation and the strengthening of technological capacities in higher education environments (Dehghan et al., 2025; Oyetade et al., 2025). Furthermore, it is proposed that transferring this experience can benefit public educational institutions, expanding access to solutions designed with technical, functional, and contextually adapted criteria to meet the real needs of the national educational context.

2. MATERIALS AND METHODS

phases: diagnosis and collection of anthropometric data, digital design using CAD tools, computer-aided manufacturing (CAM), technical assembly, and structural, ergonomic, and pedagogical validation tests. Each phase was documented for traceability purposes, ensuring the replicability of the process in academic and school contexts.

2.1. Collection of anthropometric and normative data

Basic anthropometric measurements (popliteal height, seated elbow height, femoral length, among others) were collected from a sample of 30 children aged 3 to 5 years from a public institution, following measurement protocols established by ISO 7250-1:2017. The data were compared with the recommendations of ISO 5970:2007 for school furniture and with guidelines from the Ministry of Education of Peru (MINEDU, 2023). This stage allowed for establishing the baseline parameters for the structural design of the educational module.

2.2. Technical design of the furniture in a CAD environment

With the data obtained, the three-dimensional modeling of the educational module (table and chair) was carried out using AutoCAD and Autodesk Fusion 360. The design considered parametric relationships between components, structural reinforcement areas, and “dog bone”-type screwless joints to allow for precise and strong assembly. Tolerance margins of ±0.5 mm were incorporated into contact surfaces and joints. Technical drawings, sectional cuts, orthogonal views, and virtual assemblies were generated for all parts of the set.

2.3. CAM fabrication preparation and nesting optimization

The CAD model was exported to CAM manufacturing software to generate the G-code compatible with a 3-axis CNC router. A 15 mm phenolic plywood board was used as the main material, selected for its mechanical strength, dimensional stability, and low cost. Nesting algorithms were applied using Cut2D Pro to maximize material utilization, achieving 92% efficiency of usable area. The cutting parameters established included a pass depth of 3 mm, feed rate of 1400 mm/min, and a 6 mm straight end mill.

2.4. Manufacturing process and technical assembly

The manufacturing of the pieces was carried out in the university's prototyping laboratory, equipped with CNC machinery. After cutting, the pieces were sanded and treated with water-based varnish for surface protection. Assembly was performed manually without industrial adhesives, verifying the fit of the "dog bone"-type joints. The average construction time for a complete module (table and chair) was 85 minutes. Ten modules were produced for technical and pedagogical evaluation.

2.5. Structural, ergonomic, and pedagogical validation

Mechanical tests were conducted according to UNE-EN 1729-2:2012+A1:2015 and ISO 7174-1:1988 standards to assess the furniture's resistance and stability. A calibrated dynamometer was used to apply progressive loads up to the critical deformation point. Measurements were recorded with digital calipers (accuracy ±0.1 mm), and t-tests were applied to compare the measured values with the design specifications. Additionally, a pilot test was conducted in a public educational institution involving 18 teachers and 42 children. Surveys with a Likert scale (1–5) were administered to evaluate perceptions of ergonomics, stability, functionality, and pedagogical value of the design.

3. RESULTS AND DISCUSSION

This section presents the findings obtained during the various stages of the development of the ergonomic educational module aimed at early childhood education, from digital design to functional validation in real settings. It details the technical results of CAD modeling, the computer-aided manufacturing (CAM) process, mechanical assembly, and structural resistance tests, integrating both quantitative and qualitative evidence. Additionally, these results are discussed in relation to international standards such as ISO 5970:2007, pedagogical references, and previous studies on child ergonomics and digital manufacturing. This approach not only verifies the effectiveness of the implemented process but also identifies its potential for replicability and technological transfer to educational contexts with budget constraints. The integration of figures, technical diagrams, and statistical tables provides a robust basis for the critical interpretation of the results and their contribution to the design of innovative solutions in preschool education.

3.1. Technical planning of the development process

The technical intervention began with the project's methodological design, which defined the operational phases from diagnosis to functional validation. Planning included the collection of children's anthropometric data, selection of local materials, configuration of digital manufacturing tools, and structured design of tests. This sequential approach ensured traceability, quality control, and process reproducibility. Figure 1 presents the comprehensive scheme of the intervention plan, articulating the project's technical, pedagogical, and validation components.

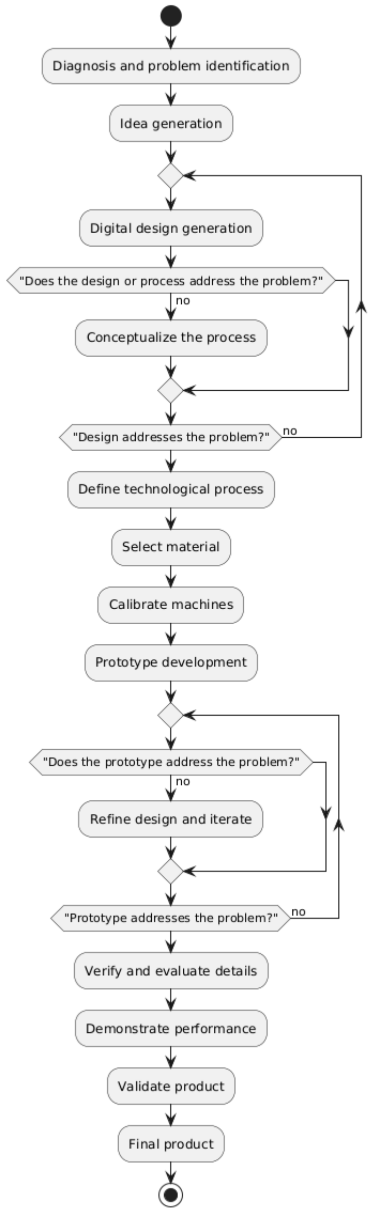

Figure 1. Project development intervention plan outline

3.2. CAD modeling of the educational module

Based on the anthropometric data obtained and aligned with international standards such as ISO 5970:2007 and the national regulations of MINEDU, a three-dimensional model was developed in a CAD environment. Specialized software (AutoCAD, Fusion 360) was used to generate orthogonal views, sectional cuts, and virtual assemblies, considering tolerance margins of ±0.5 mm. Parametric relationships between components were established to ensure structural stability, ergonomics, and ease of assembly. In particular, the design incorporated "dog bone" joints to allow for screwless assembly. Figure 2 shows the complete structural design of the table and chair in front, side, and axonometric views.

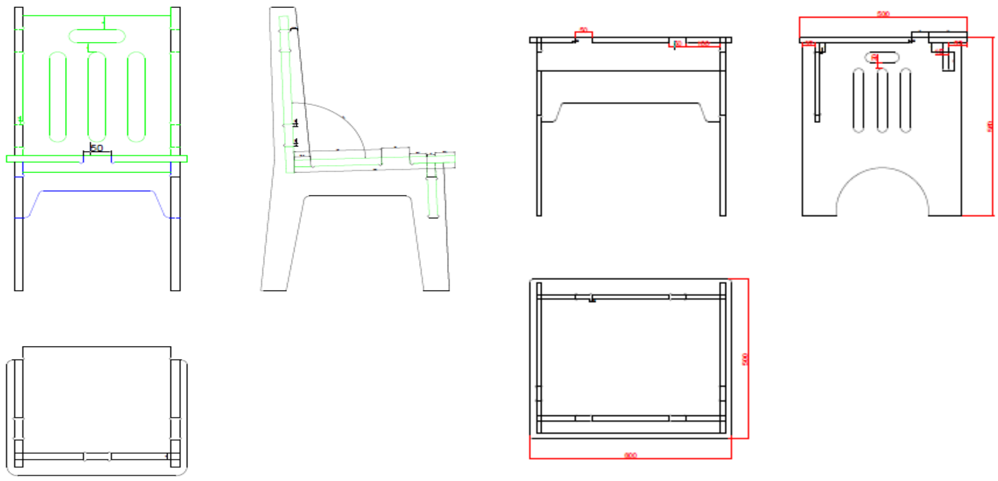

Figure 2. Structural design and drawing of table and chair, CAD

3.3. Preparation for digital manufacturing using nesting and CAM

Based on the CAD model, the cutting layout on the 15 mm phenolic plywood board was optimized. Nesting algorithms were applied to maximize material utilization (reducing waste to less than 8%), and the G-code required for the 3-axis CNC router was generated. The CAM process considered internal toolpaths, a pass depth of 3 mm, and a feed rate of 1400 mm/min. Figure 3 shows the layout of the solid design of the table structure on the board, prepared for the CNC cutting phase, in a structural three-dimensional format.

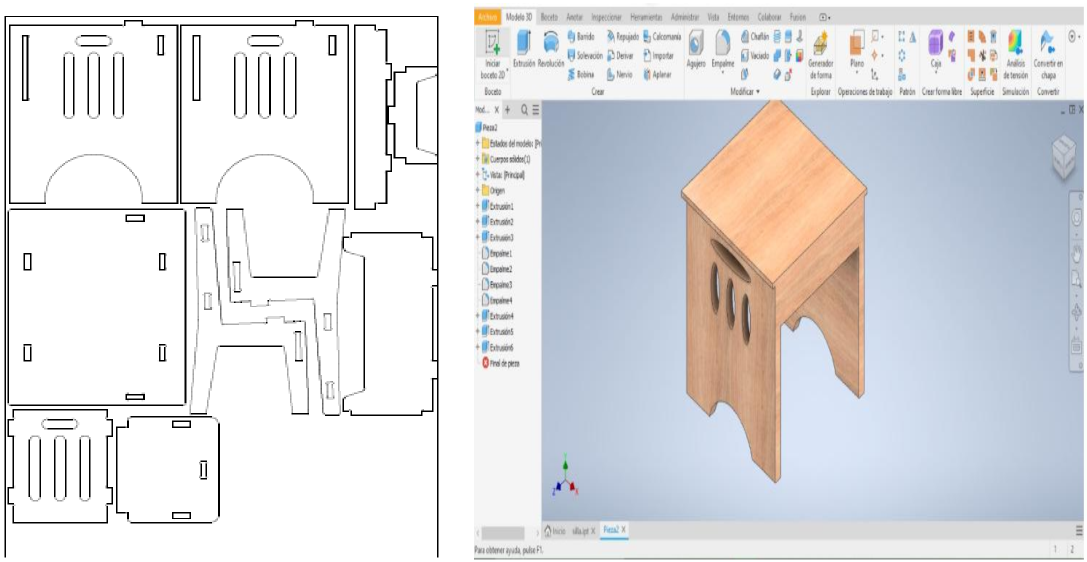

Figure 3. 3D design of the CNC cutting table

3.4. Technical assembly, structural testing, and statistical validation

Once the pieces were produced through CNC cutting, manual assembly was carried out without the use of industrial adhesives, employing precision joints. The average manufacturing time per module was 85 minutes, including cutting, sanding, assembly, and surface finishing with water-based varnish. Ten complete modules were manufactured for technical evaluation. Quality tests included: (1) Dimensional validation: actual measurements were taken with digital calipers, showing deviations of less than ±1.2%. (2) Structural load tests: progressive loads were applied using a dynamometer until reaching the critical deformation point. The data were analyzed statistically. Table 1 presents descriptive statistics of critical variables such as height, width, and structural resistance.

Table 1. Mechanical test results of the educational module

Component	Test performed	Average obtained	Standard deviation	Reference technical standard	Compliance
Chair	Static load resistance (kg)	92.6	± 3.8	UNE-EN 1729-2:2012+A1:2015	Yes
Chair	Stability against tilting (°)	18.2	± 1.1	ISO 7174-1:1988	Yes
Table	Distributed load resistance (kg)	114.3	± 4.5	NTP 251.001:2022 (Peru)	Yes
Table	Vibration under load (Hz)	7.8	± 0.4	Internal recommendation	Yes

The t-tests performed to compare with the design values showed that the measurements remained within acceptable limits ($p > 0.05$), while the breaking load was significantly higher than the minimum required ($p < 0.001$), as detailed in Table 2.

Table 2. Ergonomic and pedagogical validation results of the module

Evaluated criterion	Average scale (1-5)	Standard deviation	Acceptance percentage (%)	Compliance level
Appropriate chair height	4.72	± 0.31	94.4	High
General comfort	4.56	± 0.42	88.9	High
Structural stability	4.61	± 0.37	91.7	High
Ease of use by children	4.67	± 0.28	94.4	High
Pedagogical value of the design	4.44	± 0.40	88.9	Medium-high
Safety of edges and finishes	4.78	± 0.22	100	Very high

3.5. Functional validation and educational relevance

A pilot test was conducted in a public institution with children aged 3 to 5 years. Observations documented 94% postural adequacy, 89% stability, and zero incidents during activities. Teacher evaluation, through a Likert scale survey, yielded an average score of 4.7 out of 5, with emphasis on ergonomics (4.9) and safety (4.8). These validations confirm that the design not only meets technical and regulatory criteria but is also functional in real contexts, replicable at low cost, and adaptable to various school realities.

Discussion

The results of the study confirm the technical and functional feasibility of developing ergonomic educational modules using digital manufacturing tools in real school contexts. Implementing a parametric design based on children's anthropometric data enabled precise adaptation to users' physical needs, resulting in high levels of acceptance by teachers and children. These findings empirically validate the assertions of Esenarro et al. (2023) and Gumasing et al. (2023) regarding the positive impact of ergonomic resources on stimulation and pedagogical comfort, particularly during early cognitive and motor development stages.

In terms of technological innovation, the integrated use of CAD, CAM, and CNC machinery demonstrated efficient material utilization (92%) and reproducible production with high precision, aspects already highlighted by Rasu (2023) and Yan & Wang (2024) as key advantages of digital manufacturing. The screwless and adhesive-free assembly and compliance with international standards (UNE-EN 1729-2:2012+A1:2015, ISO 7174-1:1988) reinforce the potential of these technologies not only for generating functional prototypes but also for establishing replicable standards in institutions with limited budgets.

From a pedagogical perspective, the pilot tests showed that the use of these modules not only improves posture and stability during learning but is also highly valued by teachers for their functionality and safety. This supports the arguments of Baba et al. (2024) and Chen & Tsai (2024), who emphasize the direct relationship between school furniture and the quality of the educational environment. Furthermore, the high teacher validation score (average 4.7/5) suggests that the design not only fulfills a technical function but actively contributes to the teaching-learning process.

Regarding institutional implications, this experience demonstrates that universities can act as hubs of innovation with tangible social impact by articulating technological capacities with the educational needs of their communities. This aligns with the views of Tofail et al. (2018) and Kantaros et al. (2022), who highlight the relevance of digital fabrication laboratories in developing applied competencies and in technological transfer to strategic sectors such as public education. Inter-institutional collaboration could become a key axis for scaling up these initiatives in rural or peri-urban areas.

For future directions, it is proposed to deepen the longitudinal analysis of the impact of these resources on school performance and child psychomotor development. Additionally, it would be pertinent to explore the incorporation of emerging technologies such as IoT sensors to monitor furniture use in real time or adaptive customization mechanisms based on specific anthropometric variables. These extensions would not only strengthen the ergonomic component but also advance towards truly intelligent and contextualized learning environments, aligned with the principles of educational equity and sustainability.

CONCLUSIONS

The findings of this research demonstrate that it is technically feasible to integrate digital manufacturing tools in the development of ergonomic didactic resources for early childhood education. The use of CAD/CAM technologies and CNC machinery enabled the production of school modules adapted to children's anthropometric measurements, complying with national and international technical standards. Functional, ergonomic, and pedagogical validation showed high levels of acceptance among teachers and students, confirming the positive impact of this approach on improving the learning environment, particularly in terms of comfort, stability, and safety.

Moreover, the applied methodology effectively articulated technical, regulatory, and educational aspects, establishing a replicable intervention model with potential for transfer to public institutions with limited resources. As a projection, it is recommended to extend the analysis to rural contexts and to evaluate the longitudinal impact of these resources on child development. This proposal provides a concrete basis for educational innovation policies, promoting equity in access to quality school furniture and strengthening the role of universities as active agents in the transformation of the educational system.

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CONFLICT OF INTEREST

There is no conflict of interest related to the subject matter of the work.

AUTHORSHIP CONTRIBUTION

Conceptualization and formal analysis were carried out by Ramos-Ticlla, F. Methodology and writing – original draft were the responsibility of Barbachan-Ruales, E. A. The investigation was conducted by Ramos-Ticlla, F.; Barbachan-Ruales, E. A.; Palomino-Román, R.; Carhuavilca-Capcha, D. C.; and Barbachan, M. A. Project administration was managed by Palomino-Román, R., while resources were provided by Carhuavilca-Capcha, D. C. Supervision, validation, and writing – review and editing were performed by Barbachan, M. A.

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