

Article

Creative Upcycling of Wood Waste into Furniture: Bridging Durability Testing and Economic Viability, a Case Study

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Abstract

In this article, static durability testing is combined with an economic analysis of selected furniture manufactured from solid oak residues. Durability was assessed under the EN 1728 and EN 12520 static-load procedures, and dimensional stability was examined using statistical process-control tools (normality analysis, kurtosis and Shewhart control charts). Chairs intended for children were tested for the body mass of five-, seven- and nine-year-old children, as well as for an adult (seat force $F_1 = 250\text{--}850\text{ N}$, backrest force $F_2 = 90\text{--}290\text{ N}$). The tested chairs met the strength and durability requirements of the applied standards, and none overturned or tended to tip. A manufacturing cost and profitability analysis then quantified the cost structure. Material accounted for only 10–31% of manufacturing costs, with labour as the dominant component, reflecting the labour intensity of upcycling irregular residues into individually designed furniture. Manufacturing costs per item ranged from PLN 108 to PLN 251 against trial sale prices of PLN 250 to PLN 1300, yielding net profit margins of 46–81%. The findings indicate that upcycling post-production residues can improve the economic and potential environmental performance of furniture enterprises and support circular-economy objectives by reducing demand for virgin timber.

Keywords: post-production residues; creative upcycling; eco-design; wood waste; furniture industry; economic analysis; sustainability

1. Introduction

Protecting the natural environment is an obligation that concerns everyone. However, environmental protection and related activities are neither easy nor simple. It requires a change in thinking, the development of habits and the conviction that there is no alternative solution. The arguments for environmental protection are obvious, but the principles for implementing methods aimed at environmental protection are not so obvious. If it is possible to easily explain to end users that they should discard unnecessary things in the appropriate recycling container rather than in the trash, then producers have to change and, in some cases, fundamentally reorganise their operations. In line with the modern approach to production, it is necessary to consider at each stage what the production residues are and how they can be used most profitably. The possibilities of using production residues and post-production materials depend largely on their properties and often on their dimensions. It can be assumed that the larger and more characterised the base material, the easier the path to its full-value utilisation. However, such a material can have various uses, and the one chosen is not necessarily the right one. For instance, the peeler core is an



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excellent material for producing various goods, such as small wooden constructions, but there is ongoing research exploring how it could be developed into a hybrid plywood [1]. Most often, waste wood is used to produce particles [2]. Most waste wood is currently directed towards comminution and particleboard or fibreboard production, a recovery route reviewed in detail by Besserer et al. [3]. A key constraint of that route is that post-consumer wood frequently carries physical and chemical impurities that complicate clean recycling [4]. By contrast, in-house post-production residues are uncontaminated and of known species and grade, favouring their direct reuse in solid form. Particles from wood waste are often enriched with other lignocellulosic materials, based on research by Hua Lee et al. [5].

Among the changes forced by ecological thinking and action, one of the basic factors determining the greater involvement of producers is economics. This requires reorganisation and investment, which are obviously costs. Turning post-production waste into profit is not a straightforward task. In particular, it is very difficult to valorise very small, irregularly shaped offcuts in a way that preserves the largest possible elements of solid wood; doing so requires creative upcycling. This effort is nonetheless worthwhile, and it was deliberately undertaken in this study for two reasons: (1) to maintain the cascading use of wood, keeping the material at its highest value for as long as possible [6–8] and (2) for health-related reasons, since products made of solid wood or incorporating solid-wood elements have been associated with effects supporting human wellbeing and health [9–11].

In the face of dynamic growth in consumption and strong development across many sectors of the economy, waste generation is increasing significantly. Consequently, there is a need to seek new strategies for managing post-production waste. The EU furniture industry is a labour-intensive sector dominated by small and medium-sized enterprises and micro firms, employing around one million people in some 130,000 companies and generating an annual turnover of about EUR 96 billion [12]. At the same time, operational costs in the EU are comparatively high owing to stringent environmental, sustainability and technical standards [13], reinforcing the need for efficient use of raw materials. More broadly, the European woodworking industries—over 160,000 companies with an annual turnover of around EUR 200 billion and some 950,000 employees—present themselves as a building block of the circular bioeconomy, processing raw materials so as to minimise waste and enhance circularity [14].

In recent decades, the importance of upcycling as a response to the environmental and economic challenges of modern industry has increased. This issue has also become an important area of interest for scientists, who have studied the importance of upcycling for various sectors of the economy. Upcycling strongly aligns with the principles of sustainable development and the circular economy. The term upcycling first appeared in the literature in the 1990s. It refers to the process of reusing waste or used materials to create products of higher quality, utility or aesthetic value than the original [15,16]. According to Frankiewicz [17], upcycling is a creative recycling process that adds value to used objects and materials, transforming them into aesthetic, usable and fully valuable products. Bridgens et al. [18] argue that upcycling is the creative practice of reusing discarded materials, thereby increasing their utility, aesthetic value or social value. The authors particularly emphasise the importance of the design process and point out that upcycling goes beyond the technical framework of waste processing. Furthermore, it encompasses the relationships between designers, users and materials. Zou and Rahinah [19], in turn, argue that upcycling is a process of refining secondary raw materials by adding new value and functionality (e.g., producing furniture from pallets and building energy-efficient houses from recycled materials).

Singh et al. [20] emphasise that upcycling is a set of activities encompassing repair, modification, remanufacturing and creative transformation of unused products and materials with the primary goal of increasing their economic value. This approach underscores the market and organisational nature of upcycling as an important strategy for managing products and materials, which can be transformed or used for entirely different purposes through these activities. Furthermore, Singh et al. highlight key issues regarding the feasibility of upcycling on an industrial scale, pointing to several important factors. Among these determinants, the following were indicated in particular: increasing consumer demand for upcycled products, developing effective marketing strategies for the resulting (often 'new') products, providing eco-designers with access to secondary raw materials, developing effective collection and sorting centres for secondary raw materials in supply chains and improving the availability of upcycled products [20].

The goal of upcycling is to keep raw materials in the material and product cycle for as long as possible while maintaining their high value and mechanical properties. Given the projected shortage of wood and increasing environmental awareness, it is justified to utilise the creative processing of post-production residues in the furniture sector and shift the scientific focus towards the sustainable use of wood resources and the optimisation of their efficiency [21–23]. Furthermore, as Mojica et al. [24] point out, at the end of their first life cycle, most wood-based products retain material properties suitable for reuse or recycling in various forms. Therefore, introducing innovative upcycling methods in this industry can reduce the consumption of natural resources by turning wood waste into new furniture [25]. Processing wood by-products can also significantly reduce dependence on new wood resources while supporting local economies and sustainable practices [26,27]. Life-cycle comparisons show that the principal environmental benefit of cascading recovered wood lies in saving primary raw material rather than in direct process energy [8,28]. According to Grotowska and Beer [29], post-production waste can advance a company's bioeconomy through SMART [30] design and upcycling. These activities enable significant reductions in energy consumption and the creation of new, high-quality interior design products. This can increase product market value and enhance the competitiveness of furniture companies [31]. Furthermore, upcycling contributes to environmental protection by reducing waste and the emissions of harmful compounds.

It is also significant that such activity in the furniture industry can positively impact competitiveness. The main determinants of the growing importance of upcycling are environmental awareness, the increasing volume of waste and the high residual value of discarded furniture [32,33].

However, most recovered post-consumer wood in the furniture industry is currently used to produce wood-based panels, which can only be used for furniture components through subsequent technological processes [34]. This approach has significant drawbacks. First, processing and recycling post-consumer wood waste requires particleboard or MDF production plants to be equipped with specialised equipment for shredding (breakers) and chipping (chippers), as well as sorting (pneumatic and gravity sorters, separation cyclones) and purifying (optical sorters) wood waste. Lines for pre-processing and purifying wood waste are most often separate components of particleboard production plants. Only prepared and clean raw material in the form of recycled chips can be incorporated into the overall wood stream used for wood-based panel production, which generates significant costs [35,36].

At the same time, some recovered solid wood from both furniture and joinery can be successfully used to produce furniture made of laminated wood. The process of obtaining this type of material is significantly simpler and does not require advanced production lines [37]. Furniture producers are increasingly turning to recycled solid wood, driven by

the rising demand for upcycled products and the financial viability of such activity [38]. Recovered solid wood offers a base for original, individually designed furniture. However, a persistent barrier is the negative public perception of upcycled product quality [38], which is precisely why the mechanical parameters of such furniture require comprehensive testing. The growing interest in ecological furniture means that these products are often becoming the main elements of interior design, but they still require comprehensive testing of their mechanical parameters.

Despite growing interest in upcycling, most studies on post-consumer or post-production wood address comminution into particleboard or fibreboard [2,3,5,23,35], while the direct reuse of solid residues in load-bearing furniture, and in particular the joint assessment of its durability and economic viability, remains underexplored. This study addresses this gap. Its objective is to determine whether furniture manufactured from in-house post-production solid-oak residues meets the durability and safety requirements of EN 1728 and EN 12520 [39,40], exhibits stable dimensional performance and is economically viable at the enterprise scale. Two hypotheses were tested: Furniture (in this case, a children's chair) manufactured from upcycled solid-wood elements satisfies the strength, durability and safety criteria of EN 1728 and EN 12520 (H1). Furniture manufactured from post-production residues is economically viable, that is, its manufacturing cost is covered by market-acceptable selling prices and yields a positive profit margin (H2).

2. Materials and Methods

To assess the feasibility of products using upcycled wood, a children's chair was selected as a representative model for comprehensive testing, as its design requirements align with broader furniture design standards. The children's chair was selected as the primary durability test object because seating is the most safety-critical, load-bearing furniture category. Among the product family, the children's chair is exposed to dynamic use and the highest relative stresses, whereas tables and poufs carry predominantly static, distributed loads and are structurally less demanding. The chair thus represents the worst-case load scenario of the family, and its compliance provides a conservative durability reference. Durability was verified for the chair only; extending standardised testing to the remaining items is possible in future work.

To assess viability at the level of a real enterprise, the economic analysis was extended to a family of upcycled items produced from the same residue stream. A key element of this economic evaluation was durability testing, which served as a technical basis for a more in-depth assessment of the long-term viability of recycled wood products. The economic analysis was extended to include other furniture manufactured using the production technology used in the reference product.

The wood residues used in this study were in-house post-production offcuts and ends of solid oak (*Quercus robur* L.) generated during the enterprise's own parquet and furniture manufacturing. Being of known species and grade and free of contamination, these residues enable direct reuse in solid form and represent a closed-loop, in-house strategy rather than the recovery of heterogeneous post-consumer wood. The upcycled elements were prepared as follows: Solid oak offcuts were sorted by dimension and quality and cleaned and formatted to target module sizes. Recycled board was used for the seat structures. Elements were bonded with polyvinyl-acetate (PVAc) dispersion adhesive, class D3, formaldehyde-free, applied at 90–120 g/m² and pressed for 12 h; bonding was carried out at an ambient temperature of 18–22 °C and relative humidity of 40–60%, with a material moisture content of 8–12%. Surfaces were finished with two layers of natural oil Adler Pullex Aqua-Terra Cradle to Cradle Certified® Silver (sourced from Adler-Polska, Kraków, Poland). Apart from the adhesive and finishing oil, all materials were of secondary origin.

The recycled board was used in the seat structures as particleboard of formaldehyde-emission class E1, which ensures compliance with the requirements for materials in direct user contact. Quality control comprised the following criteria: visual and tactile rejection of cracks, knots exceeding acceptable limits, decay, discolouration and contamination; dimensional and squareness checks against nominal module sizes; verification of moisture content and its uniformity between elements; assessment of adhesive bond-line quality and joint integrity (absence of gaps, delamination or glue starvation); surface-finish inspection (uniform oil coverage, absence of roughness, cracks or unfilled voids); and, at the product level, verification of stability, structural integrity and compliance of the assembled furniture with the strength, durability and safety requirements of EN 1728 and EN 12520.

2.1. Static Load Tests on Chairs

The tests were conducted based on European standards [39,40]. In addition to the tendency of the chair to tip over, which is defined in the standards, the deformation of the backrest was measured. This deflection is significant due to the construction of the chair's components, which are made of post-production materials, and the way they are applied in the construction. However, the arrangement of the elements creating the pattern was dictated by aesthetic considerations as well. Figure 1 presents a schematic drawing and picture of the testing stand. Three chairs were used for the tests, and the tests were performed with graduated loads. The chair was placed with its back to the load, with a rear leg travel limiter. The elements used to construct the chairs were beams made of rectangular cuboids of 50 mm × 50 mm × 20 mm. Additionally, the seats were reinforced with 18 mm wood particleboard, as such elements in this arrangement cannot provide a stable load-bearing surface. The elements were bonded with Woodmax WR 13.50 M polyvinyl-acetate (PVAc) dispersion adhesive, class D3, formaldehyde-free, applied at 90–120 g/m². Woodmax[®] adhesive (sourced from Synthos, Oświęcim, Polska) holds certificates from the IFT Rosenheim Institute, confirming water resistance classes D3 and D4 and thermal resistance, as well as meeting the requirements of the IKEA IOS-MAT standard and holding ISO certificates. This ensures that users can be confident they are using a product that meets the necessary standards. The company Synthos also takes environmental considerations seriously and assesses the environmental impact of its products; Woodmax[®] adhesives are classified as eco-friendly products that contain no substances harmful to health. The surfaces were finished with natural finishing oils. Adler Pullex Aqua-Terra oil (sourced from Adler-Polska, Kraków, Poland), which is Cradle to Cradle Certified[®] Silver, was used; it is an eco-friendly wood oil based on carefully selected renewable raw materials, designed for both indoor and outdoor use and free from solvents and plasticisers, applied at 80–100 mL/m².

The feasibility of using basic beam-shaped elements has been verified in previous research [31]. Beams of different dimensions were tested in bending, and the modulus of elasticity (MOE), static bending strength (MOR) and stiffness were verified. Additionally, a quantitative two-stage analysis applying the normal distribution and Shewhart control charts was performed to check the suitability for production of the tested material. The research provided full justification and direction for creating the furniture construction of the tested beams. Furthermore, because post-production material is considered, the importance of furniture aesthetics must be ensured.

Because the material is used to produce children's furniture, the static backrest loads specified in the standard were calculated for the correct weight of boys aged five, seven and nine [41], as boys are typically slightly larger in size and weight than girls. The static strength and durability tests were performed in accordance with EN 1728 and EN 12520. The force was applied 10 times, each for 10 s. Additionally, a study was conducted on an

average-weight adult male in Poland [42]. Table 1 presents the applied seat (F1) load and back (F2) force values. The chair's tendency to tip over and its backrest deflection were measured. The force on the backrest was applied over 120–260 mm. This corresponds to the intrascapular height of the seated straight and hunched positions of boys ages five to nine [43].

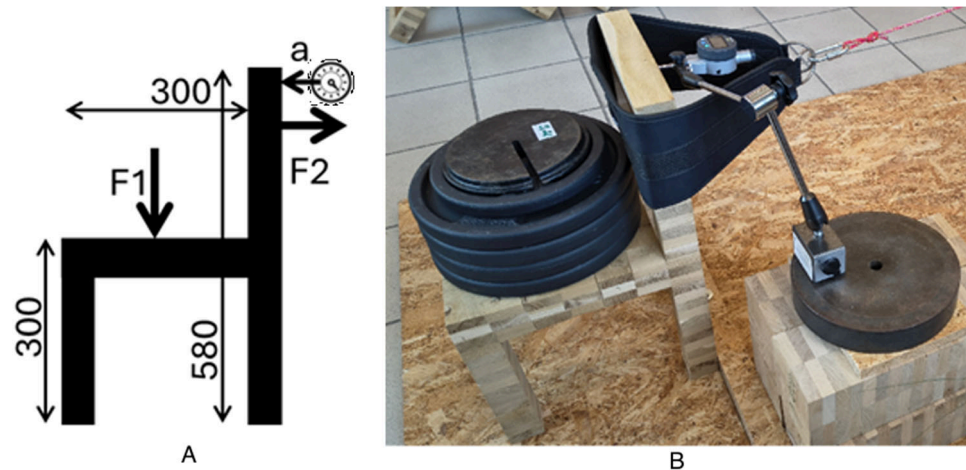


Figure 1. Seat and back static load test: (A) = schematic drawing (external profile dimensions of the chair in mm, width 300 mm, F1 = seat force, F2 = back force, a = backrest deflection meter); (B) = picture of the stand.

Table 1. Loads used in chair tests: F1 = seat load; F2 = backrest force.

Year	F1 (N)	F2 (N)	Explanation
5	250	90	Calculated proportionally based on EN
7	340	120	
9	480	160	
42	850	290	An adult man in Poland

Based on the obtained deformation measurement results, an analysis of the chair deformation results under the specified loads was conducted. The results were presented separately for each age group in the form of a box-and-whisker graph. The graph aimed to determine the general trend in the effect of user age (including weight) on the level of backrest deformation that may occur during the normal use of the furniture.

2.2. Statistical Analyses

The statistical analysis of the results involved two basic stages:

1. Creating a multivariate histogram with normal distribution analysis.
2. Developing control charts with defined control limits and specifications.

The first stage of statistical analysis of the collected empirical material was exploratory data analysis (EDA), aimed at verifying the assumptions of normal distribution in each of the four research groups [44]. The use of graphical methods combined with descriptive statistics allowed for a more comprehensive understanding of the structure of the obtained data [45].

Histograms were generated for each study group and overlaid with a normal distribution density curve. The goal was to visually assess the degree of fit of the empirical data to the theoretical model. This allowed for the rapid identification of potential outliers and the overall distribution shape, which was crucial for selecting appropriate statistical tests. For each study group, histograms were generated and overlaid with a normal distribution

density curve. Besides the overall shape, special attention was paid to two key parameters defining the morphology of the distribution: skewness, which determines the potential asymmetry of the distribution, and kurtosis, which initially assesses the distribution's flatness, classifying it as mesokurtic, platykurtic or leptokurtic [46]. The graphical procedure used was a necessary prelude to formal statistical testing. It allowed for a subjective, yet substantively justified, assessment of whether deviations from normality were significant enough to impact the reliability of subsequent analytical procedures.

In the second stage of the study, the measurement results obtained for each group were statistically analysed using Shewhart control charts. The detailed scope of the procedure employed included the following:

1. Defining the target value. A separate control chart was developed for each test group, assuming an individual target value corresponding to the arithmetic mean of the measurements obtained for a given group. Adopting individual target values was necessary because current standards are limited to a binary assessment of loads in the 'pass/fail' category. The lack of formalised guidelines regarding permissible deviations necessitated the development of a reference base based on empirical data from the authors' earlier research.
2. Determining control and specification limits. In accordance with the established methodology described in the authors' previous publications [47], the following were determined for each chart:
 - Lower and upper specification limits (LSL and USL): These limits define the tolerance range for the measured parameters.
 - Lower and upper control limits (LCL and UCL): These limits define process stability thresholds.

These values were closely linked to the statistical characteristics of the given group; their determination was based directly on the calculated mean value and standard deviation. This ensures that the limits reflect the natural process variability inherent in each analysed case.

2.3. Economic Analyses

The empirical research focused on a preliminary economic analysis of furniture products made from small pieces of wood left over from production. Four types of furniture with different functionalities were selected for analysis: a square table, a children's chair, a children's table and a pouf. First, the amount of materials and the amount of time required to produce the products were analysed. All materials originate from post-production residues: solid oak offcuts and pieces of recycled board used as seat structures. The two units refer to different processing stages: The amount of post-production residues (m^3) gives the approximate volume of loose offcuts in the bag from which the elements are cut, measured before machining and before any waste is removed. The use of wood in the product (m^2) gives the amount of finished material in each piece of furniture, which varies by product. Except for the adhesive and finishing oil, every material used was of secondary origin.

Each product was analysed separately, followed by a comparative analysis of each cost category's contribution to total production cost. In this study, the total production cost was defined as the sum of direct costs and indirect costs per product unit. Direct costs included material costs and personnel costs. Personnel costs were determined based on employees' working time and remuneration rates involved in the production process. It was assumed that the variation in labour costs resulted from the participation of employees with different experience, qualifications and hourly rates. Indirect costs were calculated as a 30% surcharge on direct costs. The adopted indirect-cost surcharge reflected the cost

burden associated with production organisation, workshop operation, administration and sales activities in the analysed enterprise.

Next, the achievable net sales revenue was compared with each product's total production cost. The financial result was calculated as the difference between these financial categories. Additionally, the margin for each product was determined as the quotient of net profit and net sales revenue multiplied by 100%. Another important element of the analysis was the comparison of the profitability of production using post-production wood residues with that of the variant assuming virgin raw materials. This allowed us to determine the extent to which upcycling affects material costs, the total production cost and the overall economic viability of the studied products. The data were presented in tabular and graphical formats.

Table 2 presents the finished furniture products analysed in terms of production economics. All components and materials used in the production of each piece of furniture, as well as the net dimensions of the pieces, are detailed. To better illustrate the form and aesthetics of the furniture under study, photos are also provided. These allow for a detailed analysis of the method and form of the post-production materials used.

Table 2. Specification of furniture manufactured using the upcycling method.

Specification	Product Photo	Amount of Post-Production Residues (m ³)	Use of Wood in Product (m ²)	Approximate Secondary Material Share (%)	Virgin Wood Share (%)
Product: Children's chair Number of elements (pcs): 146 (5 cm × 5 cm × 2 cm) and 2 (30 cm × 5 cm × 2 cm) Other materials: Wood particleboard: 30 cm × 25 cm × 1.8 cm Glue: PVAc D3 Finishing: Natural oil with Cradle to Cradle Certified® Silver		0.12	0.36	95	0
Product: Square table Number of elements (pcs): 336 (7 cm × 7 cm × 2 cm) Other materials: Wood particleboard 65 cm × 65 cm × 1.8 cm Glue: PVAc D3 Finishing: Natural oil with Cradle to Cradle Certified® Silver		0.25	1.64	95	0

Table 2. *Cont.*

Specification	Product Photo	Amount of Post-Production Residues (m ³)	Use of Wood in Product (m ²)	Approximate Secondary Material Share (%)	Virgin Wood Share (%)
Product: Children's table Number of elements (pcs): 312 (5 cm × 5 cm × 2 cm) Other materials: Wood particleboard 45 cm × 45 cm × 1.8 cm Glue: PVAc D3 Finishing: Natural oil with Cradle to Cradle Certified® Silver		0.25	0.78	95	0
Product: Pouf Number of elements (pcs): 216 (7 cm × 7 cm × 2 cm) Other materials: 6 wood particleboards 44 cm × 44 cm × 1.8 cm Glue: PVAc D3 Finishing: Natural oil with Cradle to Cradle Certified® Silver		0.25	1.1	95	0

All cost data reported in manuscript refer to the study period 2020–2023 and are expressed in Polish zloty (PLN). Because the furniture was manufactured and sold in-house, the analysis was based on actual costs incurred, not on hypothetical estimates. Labour, the dominant cost component, was valued at the hourly rates paid by the enterprise to its own manual workers over the period; these rates were consistent with prevailing national wage levels, bounded below by the statutory minimum remuneration for work, which rose from PLN 2600 gross per month in 2020 to between PLN 3490 and PLN 3600 gross per month in 2023 [48], and referenced against the average gross monthly wage in the national economy reported by Statistics Poland, which increased from approximately PLN 5167 in 2020 to PLN 7155 in 2023 [49]. Prices of materials (adhesive, finishing oil and recycled board) were taken from the price lists of wholesale suppliers applicable in the corresponding years. Indirect (overhead) costs comprised energy consumption, depreciation of machinery, wear of tools and consumables, and workspace-related costs (rent, heating and maintenance), applied at levels typical for a micro-enterprise of this profile.

No fixed profit margin was imposed on the calculations. As the study concerned the market introduction of a novel product, selling prices were not obtained by adding a predetermined mark-up to cost; instead, they were established through trial sales at the levels the market was willing to accept, and profitability was then assessed ex post by comparing the realised sales revenue with the actual manufacturing cost. The economic analysis therefore evaluated the genuine market feasibility and bioeconomic viability of the enterprise under real trading conditions, rather than the profitability implied by an assumed margin.

3. Results

The measurement results are presented in the order specified in the methodology. Measurements of differences in chair backrest deformation provided the basis for determining the validity of the economic analysis of four types of furniture manufactured from post-production wood. Although creative upcycling and eco-design govern how these residues are converted into products, their practical value depends on whether the resulting furniture is safe, durable and economically viable. Therefore, static-load durability testing and manufacturing cost analysis serve as the validation layer of the upcycling workflow, linking the design concept to measurable performance and profitability.

3.1. Static Load Tests on Chairs

In none of the tests did the chairs overturn, and in fact, they showed no tendency to tip backwards. However, some deflection of the backrest was observed. It is clear that increasing the loads acting on the backrest causes increased deformation of the backrest. The deflection values and their impact on the structure are particularly important. The results of the deformation measurements of the backrests of the tested chairs at the given loads are presented in Table 3.

Table 3. Backrest deformation measurement results (mm) (columns in relation to F1/F2).

	5 Years	7 Years	9 Years	42 Years
Test No.	250/90	340/120	480/160	850/290
1.	0.90	1.05	1.55	3.29
2.	0.88	1.04	1.54	3.20
3.	0.93	1.06	1.55	3.20
4.	0.88	1.07	1.53	3.17
5.	0.88	1.10	1.52	3.27
6.	0.89	1.00	1.53	3.25
7.	0.86	1.01	1.50	3.29
8.	0.91	1.00	1.51	3.31
9.	0.89	1.01	1.51	3.34
10.	0.88	1.01	1.51	3.33
11.	1.28	1.50	2.07	3.15
12.	1.29	1.48	2.06	3.15
13.	1.24	1.47	2.06	3.20
14.	1.22	1.43	2.05	3.03
15.	1.23	1.44	2.12	3.19
16.	1.22	1.44	2.12	3.21
17.	1.23	1.42	2.16	3.21
18.	1.18	1.44	2.11	3.27
19.	1.21	1.44	2.19	3.26
20.	1.21	1.44	2.02	3.20
21.	0.78	1.19	1.60	2.95
22.	0.83	1.17	1.60	2.95
23.	0.81	1.17	1.64	3.00
24.	0.80	1.18	1.62	3.03
25.	0.80	1.16	1.64	2.99
26.	0.83	1.18	1.64	3.01
27.	0.84	1.19	1.64	3.01
28.	0.86	1.18	1.60	3.07
29.	0.88	1.17	1.60	3.06
30.	0.86	1.18	1.61	3.00
Mean value	0.98	1.22	1.75	3.15
Median value	0.89	1.18	1.62	3.20
Standard deviation	0.18	0.17	0.25	0.12

Based on the calculated mean values, an increase in backrest deformation can be observed, which is dependent on the applied load. It should also be noted that for each group analysed, a standard deviation of no more than 0.25 mm was observed. Comparing the mean and median values further demonstrates the small discrepancy between the results. Therefore, there are no values that significantly stand out from the others. The greatest dispersion of results was observed for the group of samples corresponding to the use of five-year-olds, in which the standard deviation was approximately 18% of the mean value. Interestingly, the smallest dispersion of results was observed in Group 4, which corresponds to use by adults. The standard deviation of the results in this case was only 3.8% of the mean measured value. At the same time, increasing the acting forces did not increase the scatter of the obtained results. Based on the analysis of the values obtained for the median values for the individual age groups, the mean values are very close to the median values. This is confirmed by the small dispersion of the measurements obtained for all age groups, even though the designed chair is not intended for adults.

Statistical analysis involved comparing chair backrest deformations across four load groups. The analysis aimed to assess variations in deformation levels across all groups. A graphical representation of the test results is presented in Figure 2.

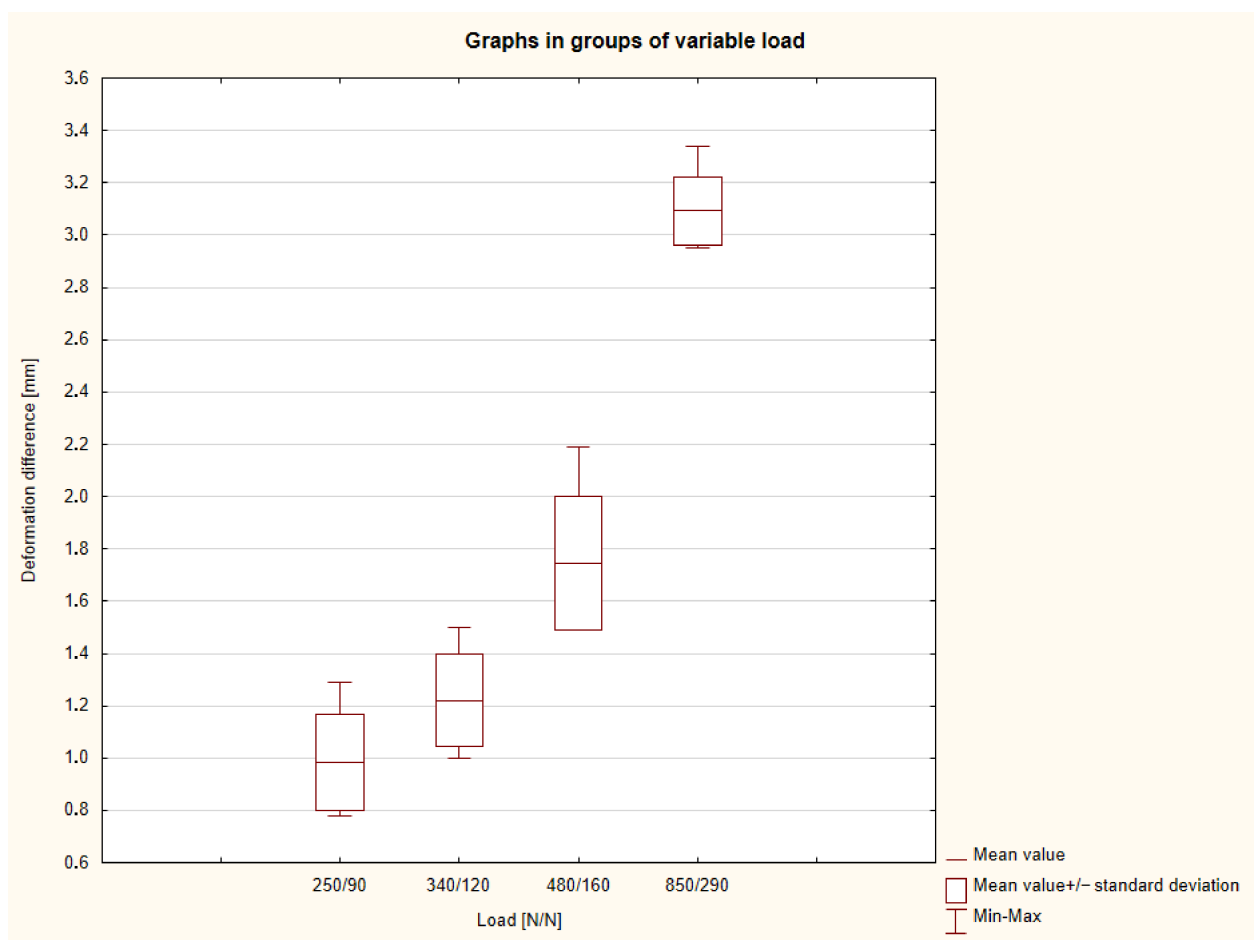


Figure 2. Box-and-whisker plot in groups for variable load: 250/90 = 5 years, 340/120 = 7 years, 480/160 = 9 years, and 850/290 = 42 years.

Based on the data presented in Figure 2, it can be concluded that individual measurement results in the individual test groups are regularly distributed around the median and mean values for the obtained measurements. The backrest deformation values do not indicate any outliers. The lowest deformation results were observed in Group 1, with an

average of 0.98 mm. A slightly higher average (1.22 mm) was recorded for Group 2. At the same time, a small scatter of 0.18 mm was observed in both groups. Therefore, it can be concluded that the tested chair is sufficiently durable when used by the intended target group (i.e., preschool children). A significant increase in deformation was observed only in Group 3 (i.e., nine-year-olds), who already exceed the weight of the intended target group. However, it should be emphasised that the designed chair meets the durability requirements even when used by an adult male with an average weight of 85 kg.

3.2. Statistical Analyses

In accordance with the adopted methodology, in the next step, an analysis of the normal distribution was performed for all tested loads, which is presented in Figure 3. The histogram was scaled at 0.2 mm for each of the tested groups.

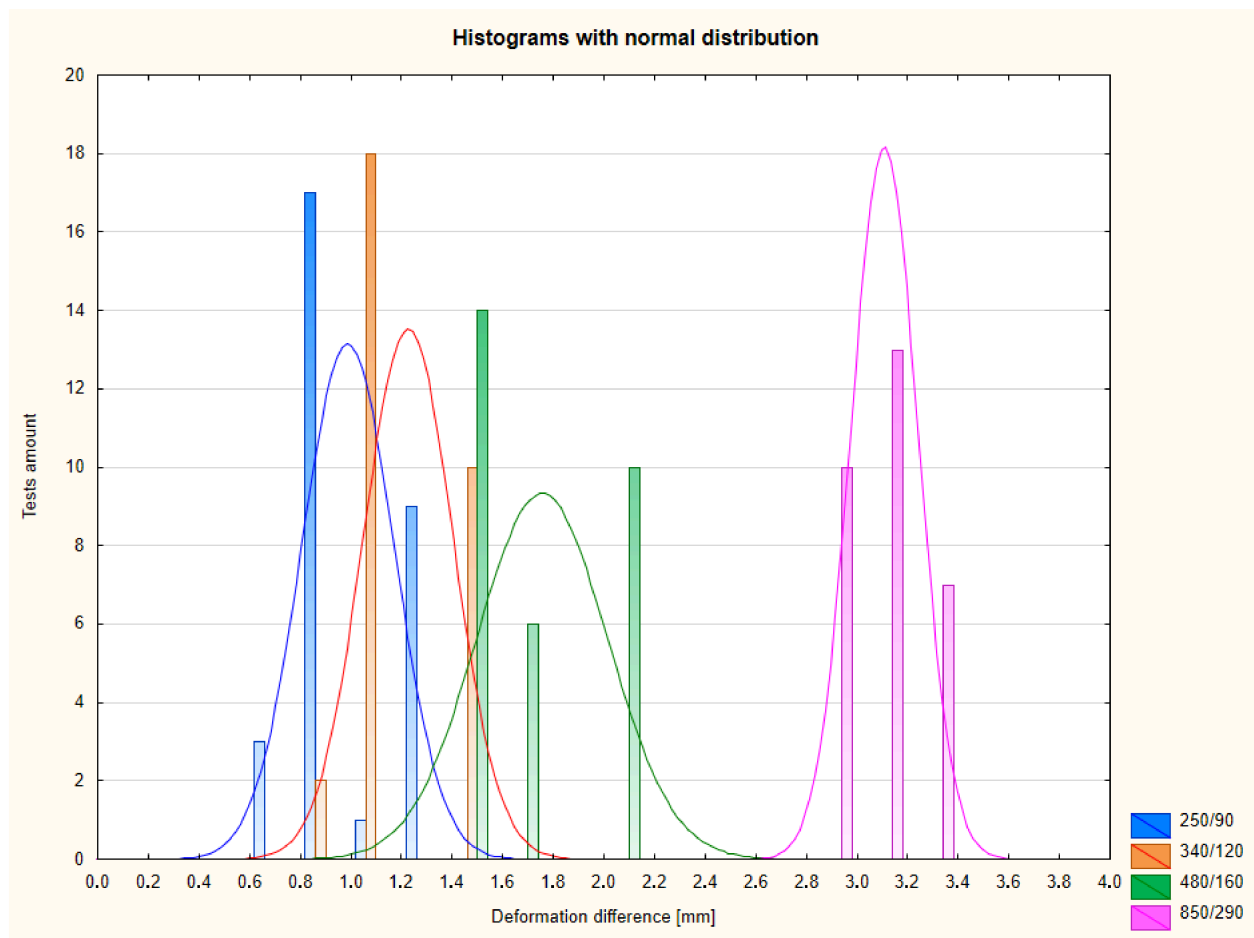


Figure 3. Histograms presented normal distribution: 250/90 = 5 years, 340/120 = 7 years, 480/160 = 9 years, and 850/290 = 42 years.

With the scale used, only Group 1 (five-year-old children) generated a four-range histogram. The remaining groups generated three-bar histograms, confirming the greater precision (repeatability) of the results in these ranges, so they meet the assumptions of Six-sigma production, which is a reference point for many manufacturers. The graph shows, based on the shape of the bars, that for child use, the results obtained are quite close to the theoretical normal distribution. The best fit to a normal distribution in the visual context was found for Group 3 (nine-year-old children). However, the target groups of five- and seven-year-olds showed the highest number of measurements close to the mean. In the case of Group 4 (corresponding to adult use), a distinct peaked distribution was visible. To

precisely analyse the normal distribution for the groups, the kurtosis and skewness values of the obtained results were calculated. The results are presented in Table 4.

Table 4. Kurtosis calculation for all tested groups.

Tested Group	Kurtosis Value	Skewness
250/90	−1.43	0.67
340/120	−1.45	0.36
480/160	−1.41	0.70
850/290	−1.32	−0.24

For all tested load groups, negative kurtosis values not exceeding −1.5 were recorded, with the highest observed in Group 4. Consequently, all groups are characterised by a platykurtic distribution, indicating that the prevalence of extreme values is lower than in a normal distribution. The skewness values for the distribution in all groups did not exceed 1 or −1, indicating that the measurements did not deviate significantly from a normal distribution. The slight negative (left-sided) skewness shown in Figure 3 suggests that the chair backrest deformations were generally lower than the mean, which may indicate greater than expected structural strength.

To more accurately verify the durability of the tested children’s chairs and determine the stability of their manufacturing process, a target (derived from the obtained mean measurement value), an upper control limit, an upper specification limit, a lower specification limit and a lower control limit were established for each test group. The adopted values are presented in Table 5.

Table 5. Values used in the Shewhart control charts.

	5 Years	7 Years	9 Years	42 Years
Name of Value	250/90	340/120	480/160	850/290
Standard deviation	0.18	0.17	0.25	0.12
Lower control line	0.45	0.70	0.99	2.79
Lower specification line	0.63	0.87	1.24	2.91
Target (mean value)	0.98	1.22	1.75	3.15
Upper specification line	1.43	1.57	2.25	3.39
Upper control line	1.52	1.74	2.50	3.51

Based on the obtained values, four Shewhart control charts were created, presented in Figure 4. Each chart presents all 30 measurements performed at the specified loads corresponding to the assumed user age groups. The adopted scale of backrest deformation differences (from 0.2 mm to 3.6 mm) was adapted to all obtained results to facilitate a visual assessment of the differences in the obtained results.

Based on the Shewhart control charts, it was found that despite the increase in loads applied to the back of the chair, the measurement results for all groups were not only within the control limits but also between the specification limits. This demonstrates the high strength and stability of the tested children’s chair backrests. It also demonstrates the high repeatability of the obtained results, enabling the precise determination of predictable results for future furniture production.

Analysis of the results for each load group showed that in the categories corresponding to use by children aged five, seven and nine, the second chair tested had the highest backrest deformation values. The exception was Group 4, which had the most similar results for all products; the maximum difference between measurements was 0.39 mm (with a maximum value of 3.34 mm and a minimum value of 2.95 mm). The high repeatability of results for

the 850 N/290 N load group likely results from the fact that adult use of the chair overloads the structure beyond its original intended use, leading to deformation limits being reached.

3.3. Economic Analyses

The evaluation presented in Table 6 reveals that the square table was the most material- and labour-intensive product. This is primarily due to its dimensions and the need to use the most material. To manufacture this table, 1.64 m² of material was used, which corresponds to 336 elements measuring 7 cm × 7 cm × 2 cm. The base of the structure was a wood particleboard measuring 65 cm × 65 cm × 1.8 cm at a cost of PLN 10. Material costs also included glue (PLN 20) and oil (PLN 20). The total labour required to construct this table was 3.5 h, resulting in personnel costs of PLN 143.

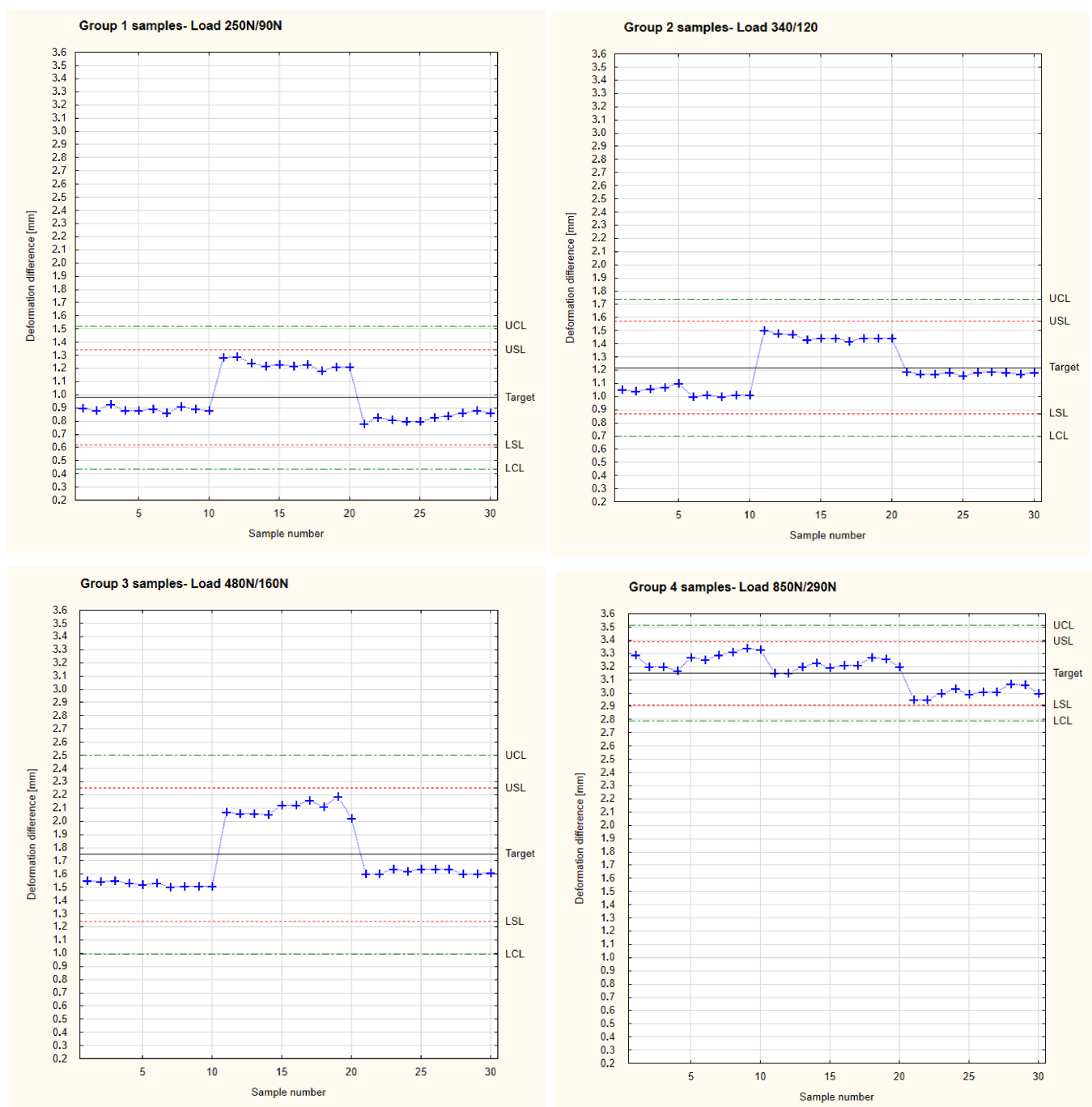


Figure 4. Shewhart control charts for four groups of samples.

Table 6. The assumed production costs of individual pieces of furniture.

Product	Wood Particleboard (PLN)	Glue (PLN)	Oil (PLN)	Labour Cost (PLN)	Working Time (h)
Square table	10.00	20.00	20.00	143.00	3.5
Children's chair	10.00	5.00	5.00	63.00	2.5
Children's table	5.00	3.00	3.00	75.00	3.0
Pouf	30.00	10.00	10.00	75.00	2.5

Another product subjected to preliminary economic analysis was a children's chair measuring 30 cm × 35 cm × 58 cm. During the manufacturing process, 0.36 m² of material was used, comprising 146 elements of 5 cm × 5 cm × 2 cm and two elements of 30 cm × 5 cm × 2 cm. Approximately 0.25 m³ of production waste was used to construct the chair. Material costs included a wood particleboard of 30 cm × 25 cm × 1.8 cm (PLN 10), glue (PLN 5) and oil (PLN 5). The total effort required to produce this table was 2.5 h, with labour costs of PLN 63.

The children's table, meanwhile, was made from 0.78 m² of material (312 squares measuring 5 cm × 5 cm × 2 cm). The raw material required for its construction came from approximately 0.5 m³ of wood waste. The construction of this product is based on a wood particleboard measuring 45 cm × 45 cm × 1.8 cm, which costs PLN 5. Glue (PLN 3) and oil (PLN 3) were also used. The manufacturing process required three hours, and labour costs totalled PLN 75. The table's dimensions were 50 cm × 50 cm × 58 cm, and its retail price was PLN 500.

The final product made from wood waste in this series was a pouf measuring 42 cm × 42 cm × 42 cm. This product was made from 1.1 m² of wood waste (216 squares measuring 7 cm × 7 cm × 2 cm). As with the larger table and the children's table, approximately 0.5 m³ of wood waste was used. The material costs also included a wood particleboard measuring 38 cm × 38 cm × 1.8 cm. The cost of this board was PLN 30, while the cost of glue and oil was PLN 10 each. Labour costs for this product were estimated at PLN 75.

As part of the preliminary economic assessment of furniture made from post-industrial waste, a cost structure analysis was conducted. Particular attention was paid to material and personnel costs, indirect costs and the total manufacturing cost (Table 7).

Table 7. Manufacturing costs of selected furniture made from wood production residues.

Product	Material Costs (PLN)	Personnel Costs (PLN)	Direct Cost (PLN)	Indirect Costs (PLN)	Total Production Costs (PLN)
Square table	50.00	143.00	193.00	57.90	250.90
Children's chair	20.00	63.00	83.00	24.90	107.90
Children's table	11.00	75.00	86.00	25.80	111.80
Pouf	50.00	75.00	125.00	37.50	162.50

The study revealed that material costs were relatively low for all analysed products. They amounted to PLN 50 for a square table, PLN 20 for a children's chair, PLN 11 for a children's table and PLN 50 for a pouf. The use of upcycled materials reduced material costs, which confirms the significant potential of upcycling to reduce wood consumption. This resource is in short supply and poses a significant challenge for companies in the wood and furniture sector. Furthermore, the cost of wood has increased significantly in recent years, necessitating the search for new supply channels and alternative uses of production residues.

Personnel costs represented the largest cost component in all analysed products, although their relative share varied substantially depending on the product type. This

confirms the high labour intensity of the production processes characteristic of upcycling. The varying labour-hour costs stem from the fact that individual products were manufactured by employees with varying experience and skills who were paid at different hourly rates. The highest labour cost was recorded for the square table (PLN 143), accounting for 57% of the total production cost while material costs accounted for approximately 20% of the total manufacturing cost. Lower but still relatively high labour costs were recorded for the children's chair (PLN 63), accounting for 58% of the total manufacturing cost while material costs accounted for 18.5%. However, for the children's table and pouf, labour costs were PLN 75 each, representing 67% and 46% of the total manufacturing cost, respectively. The lowest share of material costs was recorded for the children's table, amounting to 9.8% of the total manufacturing costs. The highest share of costs was observed for the pouf, which accounted for 31% of the production cost. These results indicate that the main factors influencing furniture production costs are labour input and the complexity of production activities rather than raw material costs.

The direct manufacturing costs of the analysed products ranged from PLN 83 to PLN 193. The lowest direct costs were recorded for the children's chair, while the highest were recorded for the square table. The direct costs were PLN 125 for the pouf and PLN 86 for the children's table. After adding indirect costs, the total manufacturing costs ranged from PLN 107.90 to PLN 250.90. The children's chair had the lowest manufacturing cost (PLN 107.90). A slightly higher total manufacturing cost was observed for the children's table (PLN 111.80) and for the pouf (PLN 162.50). The highest cost was observed for the square table (PLN 250.90).

Additionally, as part of the preliminary economic analysis, the unit profitability of the manufactured products was verified (Table 8). The highest profitability was observed for the square table. The unit net sales revenue of this product was estimated at PLN 1300. With an assumed total unit cost of PLN 250.90, a net profit of PLN 1049.10 was achieved. A net profit margin of 80.70% confirmed the high revenue potential of this product. This favourable result may be primarily due to the ability to obtain a relatively high selling price while reducing material costs by using production residues. For the children's chair, the net sales revenue was PLN 250, with a total production cost of PLN 107.90, resulting in a net profit of PLN 142.10 and a net profit margin of 56.84%. High profitability was also recorded for the children's table. Net sales revenue from this product amounted to PLN 500, while total production cost was PLN 111.80, resulting in a net profit of PLN 388.20 and a net profit margin of 77.60%. The analysis indicates that the children's table may be a particularly advantageous product in terms of the relationship between production costs and net sales price. In the case of the pouf, net sales revenue was PLN 300, while net profit amounted to PLN 137.50, allowing for a fairly high net profit margin (45.83%).

Table 8. Profitability analysis of selected furniture manufactured from post-production residues.

Product	Net Sales Revenue (PLN)	Total Production Costs (PLN)	Net Profit (PLN)	Net Profit Margin (%)
Square table	1300.00	250.90	1049.10	80.70
Children's chair	250.00	107.90	142.10	56.84
Children's table	500.00	111.80	388.20	77.60
Pouf	300.00	162.50	137.50	45.83

The next stage of the research compared the profitability of selected products manufactured from primary wood materials rather than post-production residues (Table 9). This analysis confirmed a significant change in the total manufacturing costs of all analysed products, although this change varied. The increase in material costs, determined based

on the amount of raw material used and the unit price of PLN 100.00/m², resulted from the need to include the cost of the virgin raw material. The highest total manufacturing cost was recorded for the square table (PLN 414.90). Despite the significant increase in production costs, this product still achieved the highest net profit of PLN 885.10 and a net profit margin of 68.08%. Compared to the variant using wood production residues, the margin decreased from 80.70% to 68.08%. For the remaining products, profitability also decreased. For example, the net margin for a children's chair dropped from 56.84% to 42.44%, while that for a children's table dropped from 77.60% to 62.04%. Due to the relatively high consumption of primary raw materials in the pouf, this product experienced the largest decline in value, from 45.83% to 9.16%.

Based on the preliminary analysis, it was confirmed that the profitability of production using post-production waste largely depends on effective work organisation and the ability to reduce the time required for production processes. Furthermore, the possibility of achieving a higher selling price resulting from the unique nature of the manufactured products is important. Products with lower total production costs, such as the children's chair and table, showed greater flexibility and greater resistance to demand fluctuations. The pouf, while still profitable in its recycled version, proved more sensitive to increased material costs when using virgin raw materials. However, products with higher total costs (e.g., the square table) require appropriate market positioning (e.g., as limited-edition items or with increased aesthetic value) to ensure a positive margin and the economic viability of production.

Table 9. Profitability analysis of selected furniture made of raw wood material.

Product	Net Sales Revenue (PLN)	Total Production Costs (PLN)	Net Profit (PLN)	Net Profit Margin (%)
Square table	1300.00	414.90	885.10	68.08
Children's chair	250.00	143.90	106.10	42.44
Children's table	500.00	189.80	310.20	62.04
Pouf	300.00	272.50	27.50	9.16

The results indicate a clear economic advantage of upcycling in the analysed case, providing a starting point for a broader discussion of the potential for implementing this method in the furniture industry. These results are consistent with the conclusions of Besserer et al. [3] and De Klerk et al. [50], who point to upcycling as a strategy generating significantly higher added value than conventional material recycling. The results published in Grotowska et al. [31] confirm these conclusions in the conditions of a real-world manufacturing enterprise.

However, it should be noted that the presented analysis is based on economic data from a specific company that has been operating in the market for several decades and has a well-established, recognisable micro-brand in its narrow production segment. Therefore, the analysis excludes marketing and promotional costs, as the firm does not incur them—its market position is based on its long-standing reputation and loyal customers. Similarly, packaging costs are zero, as the workshop uses only used cardboard boxes sourced from suppliers who would otherwise throw them away. This practice aligns with the zero-waste policy and generates no additional costs. The analysis presented is illustrative, and the entire design and implementation approach is scalable and, as such, should be considered a universal example of a possible business model.

4. Discussion

The combination of empirical research with economic analysis enables a full assessment of where the development of production residues is headed. The reuse and economic viability of production residues should be assessed, since environmental and profitability considerations jointly determine whether such practices are adopted. The environmental advantages discussed are qualitative, as this study does not quantify ecological performance; such quantification through a full LCA is left for future work. Both hypotheses were confirmed. The tested chairs met the strength, durability and safety criteria of EN 1728 and EN 12520 across the full load range, from a five-year-old child to an adult, without overturning and with backrest deflection not exceeding ≈ 3.3 mm, thus supporting H1. Manufacturing costs of PLN 108 to PLN 251 were covered by market-acceptable selling prices of PLN 250 to PLN 1300, yielding net profit margins of 46–81%, which confirms the economic viability of furniture made from post-production residues in the enterprise studied and thus supports H2.

While the conclusions drawn from this research result from the specific production analysed in this study, they can also serve as a source of knowledge for other entrepreneurs:

1. The tested chairs passed tests carried out based on EU standards regarding test methods for determining durability. The three tested chairs met the durability requirements of EN 1728 and EN 12520: under static loads scaled from a five-year-old child to an adult (seat force 250–850 N, backrest force 90–290 N), none overturned or tended to tip backwards, and backrest deflection remained low, rising from ≈ 0.9 mm to ≈ 3.3 mm across the load range.
2. The obtained research results and the mean and median values calculated from them are very similar. The target groups for five- and seven-year-old children were 0.09 mm and 0.04 mm, respectively. This indicates a small dispersion of results, which was confirmed by a normal distribution.
3. The Shewhart control charts showed a general effect that, despite the increase in loads applied to the back of the chair, the measurement results for all groups were not only within the control limits but also between the specification limits. This means the stability of the structure and the stability of the expected production effects.
4. The research indicates that material costs account for a small share of the product's manufacturing costs (ranging from 10% to 31%). This was due to the use of raw materials derived from post-production wood waste in the manufacturing process. Personnel costs, however, dominated the manufacturing cost structure, driven by the significant labour intensity of creative upcycling processes.
5. The use of virgin wood as a raw material increased total production costs and reduced the net profit margin for each product. The largest effect was observed for the pouf, whose margin decreased from 45.83% to 9.16%.
6. The manufacturing cost per item ranged from PLN 107 to PLN 250 against trial sale prices of PLN 250 to PLN 1300, giving gross margins of 46–81%; the lowest margin (pouf, 46%) and the highest (square table, 80.8%) delimit the profitability range observed for this product family.
7. The research results confirm that the efficiency of work organisation largely determines the profitability of furniture production based on the reuse of post-production waste. The opportunity to obtain a higher product price due to its high environmental friendliness and unique design, which results from the use of creative post-production waste processing, is also significant.
8. Reusing raw materials to create furniture with interesting designs not only offers economic but also environmental benefits. The wood and furniture sector has been

facing significant challenges for years, including a shortage of wood and rising prices, which can negatively impact the industry's competitiveness in external markets.

The results of this case study are consistent with and extend previous work on wood-waste valorisation. The dominance of labour over material cost reflects the labour intensity characteristic of craft-based upcycling, in which irregular residues are individually sorted, formatted and assembled into finished products [32,33]. This cost structure contrasts with the panel- and fibre-oriented recovery routes that dominate the literature [2,3,5,23,35] and with cascading-use analyses of wood furniture, which address the value retention of existing stock rather than new production from residues [7,8]. Compared with studies examining the reuse of solid wood in laminated timber and panel products [37,51], the present work adds a combined durability and economic evaluation for finished, load-bearing furniture manufactured within a single enterprise.

Two findings are of particular practical relevance. First, the tested children's chairs met the strength and durability requirements of EN 1728 and EN 12520, indicating that upcycled solid-wood elements, complemented by recycled board in the seat structures, can satisfy the criteria applied to conventional domestic seating. This finding directly addresses the barrier identified in the literature, where the negative public perception of upcycled product quality is reported as a persistent obstacle to scaling furniture upcycling [38]. By demonstrating compliance with the same standards applied to conventional domestic seating, the present results provide objective evidence of quality. Second, because material accounted for only 10–31% of total manufacturing costs, the economic viability of this model depends chiefly on labour efficiency rather than on material supply, which has direct implications for scaling such production in micro, small and medium-sized enterprises. The two dimensions are linked in the pricing mechanism. Confirmed compliance with EN 1728 and EN 12520 establishes the durability and reparability that validates the products' positioning as long-lasting, individually designed pieces, and it is this positioning that made the achieved selling prices acceptable to the market: the square table sustained a price of PLN 1300 against a manufacturing cost of PLN 250.90. Structural performance is therefore not independent of the economic outcome but a precondition for the price the market accepted, although the present data do not allow the size of this premium to be quantified against an untested reference product. The environmental advantages discussed here are qualitative: Because no life-cycle assessment, carbon accounting or energy balance was carried out, this study does not quantify ecological performance.

This study has several limitations that define the scope within which its conclusions hold. First, it is a single-company case study, which constrains generalisability to other enterprises and markets. Second, the durability assessment is based on three chairs, so statistical inference is limited; the results are reported for this sample rather than as population-level evidence. Third, no life-cycle assessment, carbon accounting or energy balance was performed, so environmental benefits are discussed qualitatively only. Fourth, the tests were short-term static strength and durability tests; long-term durability, fatigue and creep behaviour were not evaluated. Fifth, the products are not made exclusively from solid upcycled wood, as the seat structures incorporate recycled board, which should be taken into account when interpreting the mechanical results. Finally, the economic analysis reflects market-specific selling prices established through trial sales during the period 2020–2023 and enterprise-specific cost conditions, which may not transfer to other markets or firms. These limitations indicate directions for future work, including a full life-cycle assessment, long-term mechanical testing, a comparison of alternative bio-based adhesives within a fixed product design, and validation across additional enterprises and product types. Further research could focus on designing additional products from other types of

waste while simultaneously optimising assembly time and automating selected production stages, thereby further increasing the price competitiveness of upcycled furniture.

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