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Article

Determination of Reliability of Selected Case Furniture Constructions

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Abstract: The reliability of furniture constitutes one of the most important features taken into consideration when buying furniture. However, to evaluate furniture reliability, furniture manufacturers often rely on their own experiences and common patterns without the usage of specialized tools. The presented work aimed to develop a mathematical apparatus to be used in a specially created web application that would enable the calculation of the reliability of the selected furniture joints and whole case furniture structures. This paper describes the functionality features of the newly created web application, which could be used in the furniture industry practice providing a valuable support tool for engineering works. In this paper, the reliability calculations are presented for the examples of furniture eccentric joints and case-type furniture made of those joints. Two different materials, namely MDF and laminated three-layer particleboard, of 18 mm are considered. The achieved results confirm the higher reliability of the furniture eccentric joints made of MDF of 18 mm in comparison to the furniture eccentric joints made of particleboard of the same thickness. The calculations of reliability for the analyzed construction of furniture confirmed also that the reliability improved when the parallel reliability structure was adapted. That was the case for both the MDF and laminated three-layer particleboard.

Keywords: case furniture; reliability; durability; web application

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1. Introduction

In general, the quality of furniture is defined as a system of sets of aesthetic, functional, technical, material, technological, ecological, and other properties. The specific composition of this system of the set is dynamic, because it is possible to adjust this set for different ways of evaluating furniture, and individual elements can have different relevance. The more elements the set has and the more precisely the relevance of individual elements is determined, the more accurately the quality of the furniture will be evaluated in terms of the level of the given requirements. From an objective point of view, the product is of high quality only if all elements of the set meet the agreed parameters. Each element in the set has an importance (relevance) that corresponds to the degree of the required quality. It is necessary to realize that even with the most objective determination of the relevance of individual elements, it is not possible to achieve complete agreement with the consumer's opinion because each consumer understands the quality of the product from his/her point of view [1]. Nevertheless, in several studies investigating the determinants of customers' choices when purchasing furniture [2–7], authors indicate a set of properties that receive the highest priority. Among those desirable features of furniture items, furniture durability which includes also their reliability is listed. In the work [8], it is pointed out how essential the strength and durability features are to meet the requirements of the contemporary furniture market. At the same time, it highlights that the failure in furniture is often attributed to its joints, which are the weakest link in the structure. Therefore, the engineering data on the strength of furniture joints have key importance for designing and redesigning the products in the furniture industry to meet product strength and durability [9]. Thus, it is crucial for the manufacturers to be able to evaluate the reliability of both the joints and the whole furniture items they produce [10].

Reliability is the property (ability) of furniture to perform the required functions in a specified time while maintaining the operating parameters given by the technical conditions; it is expressed by partial properties, such as failure-free service life and repairability. From the point of view of reliability, furniture construction is considered a multi-component system. In a multi-component system generally, we find the reliability of each component, each of which may be treated as a system itself, and then knowing the structure of the system and using probability concepts, the reliability of the complete system may be evaluated [1,11]. According to [12], the reliability indicators can be divided into five directions according to the theoretical approach and application goals:

- Probabilistic reliability analysis (PRA);
- Phenomenological theory of reliability;
- Interference theory of reliability (ITER);
- Synthesis of fracture mechanics and reliability;
- Corrected theory of reliability.

There is no universal practical procedure for estimating the reliability of a complex mechanical structure. Mathematical theories of reliability are in a state of development, and the preparation of specific documents for the quantification of reliability is insufficient [12]. Regardless of the reliability estimation method, it is necessary to obtain data from two areas, the area of operational load and the area of properties of the used material. In addition, it is necessary to choose a suitable hypothesis (model) that would combine the data from these two areas. In this way, operational load characteristics and material characteristics will be brought into context, while the desired reliability (lifetime, strength) will be the result.

The basic idea of ITER is the analysis of the properties of simultaneous random variables, one of which quantifies the ability of the furniture structure (load-carrying capacity, strength) and the other the operating mode during the lifetime. In the system of the interference theory of reliability, strength and stress working on it are taken into consideration for evaluation of its reliability. By models here we mean mathematical models, in particular probabilistic models. The mathematical models used in reliability theory can be broadly divided into three groups: time-dependent models, stress–strength (S–S) models or interference models, and time-dependent S–S models. For time-dependent models, stress is not taken into consideration, whereas for S–S models time is not considered; but, it does not mean that the other factor is not present; it is simply neglected, or its effect is negligible. In time-dependent models, both time and stress are taken into consideration. In the work [12], these two quantities are dynamized, that is, the dependence on time is expressed.

The reliability of the furniture construction can also be expressed through its safety. By the term safety, we understand the property of the product not to endanger human health or the environment, when performing the specified function during the specified time and under the specified conditions. In the narrower sense of the word, it expresses sufficient strength and stiffness of the construction. In practice, the term safety also has a wider meaning and is intertwined with the definition of reliability. For furniture construction, it is also connected with the length of the failure-free service life of the products, which means the durability of the furniture. The reliability of furniture can be achieved by its appropriate dimensioning, by using one of the methods of construction mechanics. The most appropriate is the method of limit states, where the basic reliability criterion is the achievement of a decisive limit state. A limit state is considered to be a state in which the furniture construction loses the necessary properties to fulfil its purpose safely and satisfactorily according to operational requirements. The method of limit states is the method of extreme values. It belongs to semi-probabilistic methods because it also uses deterministic approaches.

In the subject literature, there are works investigating the safety and durability issues of case-type furniture in the context of the strength and stiffness of its construction [13,14]. The work [15] investigated corner joints made of 18 mm MDF and three-layer particleboard, while the work [16] studied corner joints made of OSB. In the study [17], L-shape furniture joints produced from OSB material of different densities (OSB-I, OSB-II, OSB-III) were investigated. Additionally, single-staple joints produced from those materials were studied [18]. There are also works dedicated to the broadly understood subject of the durability of the entire structure of case furniture, for example, the durability of case furniture from the point of view of the size of the load and the number of joints [19], as well as durability of the case furniture subassembly [20]. The work [21] investigated the durability of kitchen furniture when a change in heat and humidity occurs. However, there are only a few works dedicated to the topic of the reliability of the entire structure of case furniture. The reliability of case furniture in the context of the distribution of the strains and strength of the furniture joints, having an impact on the reliability of the whole furniture construction, is investigated in the study [22]. In the study [23], the kitchen cabinets were investigated in terms of maximum load-carrying capacity. The cabinets were manufactured on a scale of 1:1 and loaded until failure happened.

As indicated earlier, the durability of the furniture is recognized among the most important factors influencing the decision on buying furniture. Thus, to provide the product durability that customers require, manufacturers must ensure the reliability of the furniture they manufacture. Therefore, despite the obligation of a 2-year warranty period, required by the European Union regulations towards the manufactured products, on the furniture market, there is a tendency to design and produce furniture with a longer period of failure-free work, and in some cases to offer even an extended warranty period. The extended warranty is also used as a marketing tool to minimize the risk when buying long-term goods, such as kitchen furniture [24,25].

Research [26,27] shows that furniture manufacturers often do not use a mathematical apparatus to determine the reliability of manufactured furniture and, above all, they rely on their own experiences and common patterns. To meet the needs of enterprises, it would be beneficial to develop a mathematical apparatus allowing to determine the reliability of the whole furniture construction. This would be possible only after determining the reliability of individual joints. As the reliability of furniture construction has a direct impact on the durability of the furniture structure [22,28], the aim of the presented work was to develop a mathematical apparatus to be used in a specially created web application that would enable the calculation of the reliability of the selected furniture joints and whole case furniture structures and thus enabling the determination of the durability of the analyzed constructions.

2. Materials and Methods

The works on the creation of the mathematical apparatus and a web application enabling the determination of the reliability and duration of the warranty period were completed within the BaltSe@nioR project. The project aimed at equipping furniture manufacturers with new knowledge and tools facilitating the creation of furniture that is aging-friendly, thus not only safe and aesthetically pleasing, but also durable. As mentioned above, the reliability of the entire furniture can be calculated by taking into account the reliability of its individual furniture joints. Thus, the first stage of the investigation was dedicated to the reliability testing of selected cabinet furniture joints. Altogether 3600 samples of furniture joints were subjected to the reliability tests performed on a dedicated laboratory stand. The samples were made from laminated three-layer particleboard and MDF of 16, 18, and 22 mm in thickness. The furniture joints were manufactured by the professional furniture manufacturer Paged Meble S.A. (Poland). The quality grade of wood-based boards used to manufacture the furniture joints was in accordance with the standard [29]. Three types of mechanical connectors joining the elements of the samples were investigated; those included confirmat screws (Ø5 × 50 mm), dowels (Ø8 × 32 mm), and eccentric joints

(Minifix type Ø15 × 14,6 mm). Each of those configurations was represented by 200 testing samples (as presented in Table 1).

Table 1. The number of testing samples made of various materials, connectors, and thickness of the elements of the furniture joints.

		Confirmat Screws	Dowels	Eccentric Joints
MDF	16 mm	200	200	200
	18 mm	200	200	200
	22 mm	200	200	200
Particleboard	16 mm	200	200	200
	18 mm	200	200	200
	22 mm	200	200	200

The shape and dimensions of the tested samples are shown in Figure 1. Polyvinyl acetate (PVAc) adhesive was used for the joint with the dowel. The confirmat screws and eccentric joints were screwed under application of the same moment of 2.5 Nm with a torque wrench.

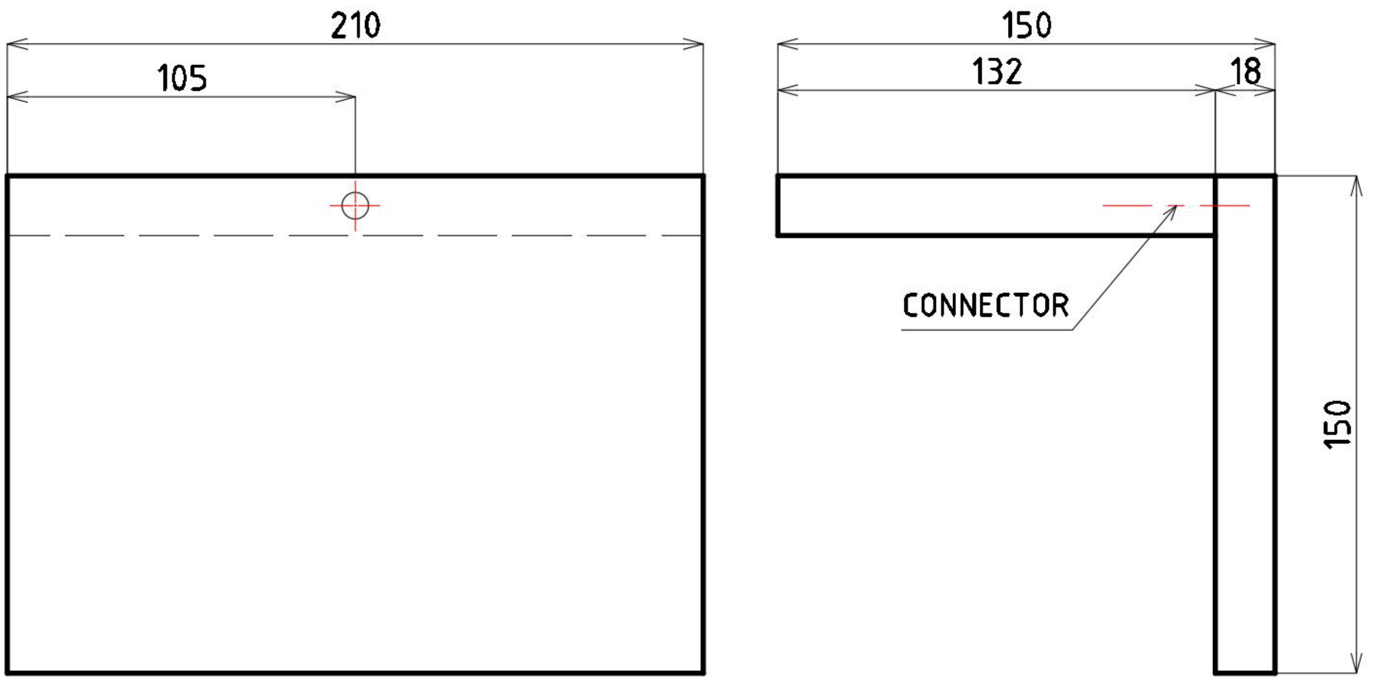

Figure 1. The shape, dimensions, and the loading of a case-type furniture sample used in the reliability tests (dimensions are given in mm).

The reliability testing of the joints was a necessary research step as the reliability characteristics of the furniture's individual joints are the main source of safety risk and durability of the use of the furniture. Usually, case furniture is treated as serial structures of connected constructional nodes [27]. It is assumed that an object (a piece of furniture) has a serial structure in terms of reliability when all its elements (construction nodes) are operational. In other words, the failure of one structural node leads to the failure of the entire system. In a mathematical notation, a serial structure is presented by the equation [30]:

$$R(t) = \prod_{i=1}^{m} R_i(t). \tag{1}$$

The above mathematical notation means that damage to at least one structural node causes damage to the entire piece of furniture. A more advantageous solution from the point of view of reliability is the use of a parallel system, which remains reliable if at least one of its elements (structural nodes) remains operational [31]. In formal terms, a parallel system is presented as follows:

$$R(t) = 1 - \prod_{i=1}^{m} [1 - R_i(t)]. \tag{2}$$

Thus, the use of several elements intended to perform the same function and connected in a parallel system in terms of reliability is an effective way of increasing (reserving) the reliability of the entire piece of furniture. In practice, additional elements connected in a parallel system to the basic ones can be used for joining elements of case furniture, e.g., when the primary connector of the furniture joint is an eccentric connector, an additional connector can be added.

To determine the reliability of case furniture, the next step was to establish the groups of statistical distributions. The following distributions were taken into account [32]:

- Exponential distribution with the density function:

$$f(x) = e^{-x}, \tag{3}$$

- Gamma distribution with the density function:

$$f(x) = \frac{x^{a-1} e^{-x}}{\Gamma(a)}, \tag{4}$$

- Log-normal distribution with the density function:

$$f(x) = \frac{1}{sx\sqrt{2\pi}} e^{-\frac{\log^2 x}{2s^2}}, \tag{5}$$

- Weibull distribution with the density function:

$$f(x) = cx^{c-1} e^{-x^c}. \tag{6}$$

In all of the above cases, the variable x was appropriately shifted and scaled using the parameters x_0 and λ, so in the above formulas everywhere, instead of x, a more general expression was used:

$$\frac{x - x_0}{\lambda}. \tag{7}$$

Moreover, in the gamma distribution, there is a shape parameter a, in the log-normal distribution, there is a standard deviation s, and in the Weibull distribution, there is a shape parameter c.

3. Results and Discussion

For the investigations, a virtual model of case-type construction consisting of four elements, bottom, top, and two side walls, was adopted. The overall dimensions of the construction were 2000 mm high, 800 mm wide, and 550 mm deep. Two variants of construction materials have been chosen: an 18 mm thick MDF board and an 18 mm thick laminated three-layer particleboard. The connections of the top and bottom with the side walls were made using eccentric connectors, two for each joint.

The data obtained from the laboratory reliability tests of furniture joints made of MDF and particleboard of 18 mm constituted the input base research material. The reliability of individual joints was calculated using Weibull++ software. The comparison of the reliability results for MDF and particleboard of 18 mm is presented in Figure 2.

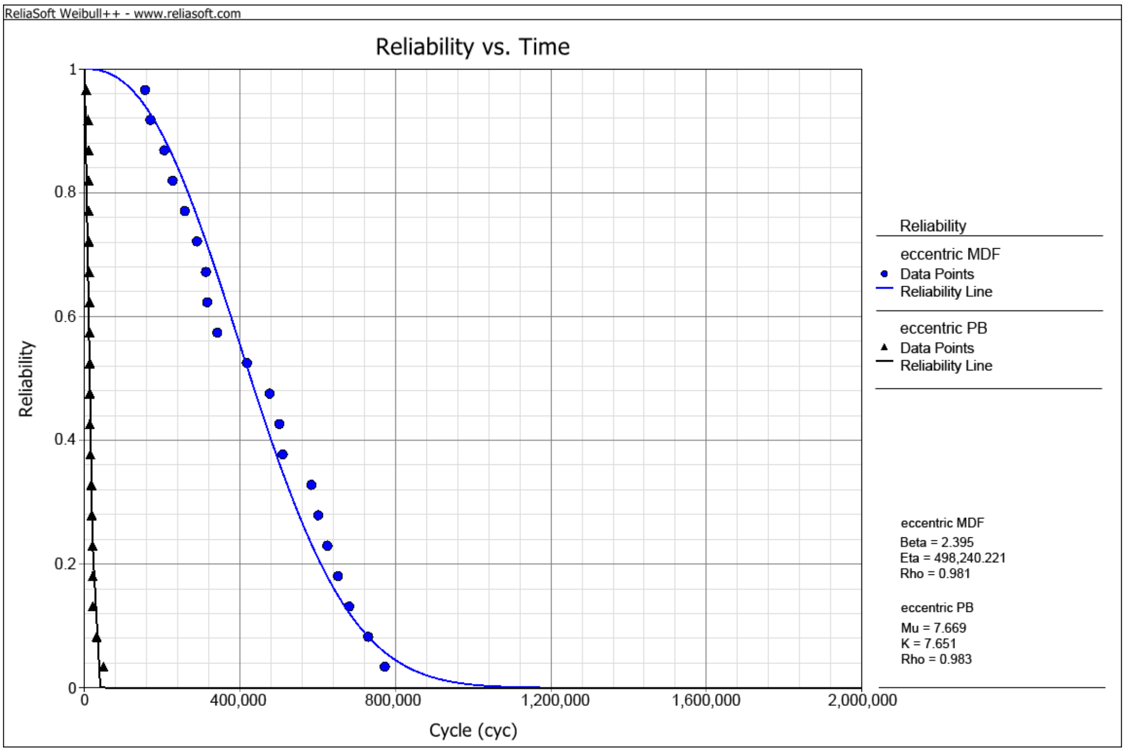

Figure 2. The comparison of the reliability of case-type furniture eccentric joints made of MDF and particleboard of 18 mm.

The obtained results confirm the higher reliability of the furniture eccentric joints made of MDF of 18 mm in comparison to the furniture eccentric joints made of particleboard of the same thickness. This is caused by a more consistent structure of the MDF. The achieved results are also in line with the results of [15]. This stage of the investigation concerned the reliability of individual joints. In the next step, the entire construction of selected case-type furniture was considered.

To make it possible to calculate the reliability of entire furniture structures on the basis of data on the reliability of individual joints and the type of structure connecting construction nodes, a mathematical apparatus was developed. The analytical process of conducted calculations is presented below.

In order to evaluate the reliability of the whole case-type furniture constructions for each of the distributions mentioned in Materials and Methods, the parameter values were determined that best fit the Probability Density Function (PDF) to the empirical data. For this purpose, the Maximum Likelihood Estimation (MLE) method was used, the operation of which is as follows.

Let the random variable X have the density $f_\theta(x)$, where θ is the (potentially vector) parameter of the distribution. Assuming that the sample $X_1, X_2, \ldots, X_n$ from the distribution of this variable is given, the total sample density as a function of the parameter (likelihood function) can be described by the formula:

$$L(\theta; x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} f_\theta(x_i)\,. \tag{8}$$

The maximum likelihood estimator of the parameter θ is the statistic $\hat{\theta}$, for which the likelihood function satisfies the condition:

$$L\left(\hat{\theta}; x_1, x_2, \ldots, x_n\right) = \sup_{\theta} L(\theta; x_1, x_2, \ldots, x_n), \tag{9}$$

for each of the points $(x_1, x_2, \ldots, x_n)$.

As an example, a sample $X_1, X_2, \ldots, X_n$ from the normal distribution with the expected value μ and the variance σ^2 can be considered. The density of this distribution is equal to:

$$f_{\mu,\sigma^2}(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad (10)$$

so the likelihood function is given as:

$$L\left(\mu, \sigma^2; x_1, x_2, \ldots, x_n\right) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x_i-\mu)^2}{2\sigma^2}} = \frac{1}{\left(\sqrt{2\pi}\sigma\right)^n} e^{-\frac{1}{2\sigma^2}\sum_{i=1}^{n}(x_i-\mu)^2}. \quad (11)$$

As it takes only positive values (as the product of all positive density functions), to simplify the calculations, the logarithmic function increasing on $\mathbb{R}_+$ can be used:

$$l\left(\mu, \sigma^2; x_1, x_2, \ldots, x_n\right) = \ln L\left(\mu, \sigma^2; x_1, x_2, \ldots, x_n\right) = -\frac{1}{2\sigma^2}\sum_{i=1}^{n}(x_i-\mu)^2 - \frac{n}{2}\ln\sigma^2 - \frac{n}{2}\ln(2\pi). \quad (12)$$

To find its maximum, the partial derivatives are equated to zero with respect to the parameters:

$$\frac{\partial \ln L}{\partial \mu} = \frac{1}{\sigma^2}\sum_{i=1}^{n}(x_i-\mu) = 0, \quad (13)$$

$$\frac{\partial \ln L}{\partial \sigma^2} = \frac{1}{2\sigma^4}\sum_{i=1}^{n}(x_i-\mu)^2 - \frac{n}{2\sigma^2} = 0. \quad (14)$$

The solution is the values:

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} x_i = \overline{x}, \quad (15)$$

$$\hat{\sigma}^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i-\overline{x})^2. \quad (16)$$

To determine whether the found point is in fact a maximum, the following procedure was applied: At this point, the function l takes the value:

$$l\left(\hat{\mu}, \hat{\sigma}^2; x_1, x_2, \ldots, x_n\right) = \ln L\left(\hat{\mu}, \hat{\sigma}^2; x_1, x_2, \ldots, x_n\right) = -\frac{n}{2}\ln\hat{\sigma}^2 - \frac{n}{2} - \frac{n}{2}\ln(2\pi). \quad (17)$$

The following difference was considered:

$$\begin{aligned} l\left(\hat{\mu}, \hat{\sigma}^2; x_1, x_2, \ldots, x_n\right) - l\left(\mu, \sigma^2; x_1, x_2, \ldots, x_n\right) &= -\tfrac{n}{2}\ln\left(\tfrac{\hat{\sigma}^2}{\sigma^2}\right) - \tfrac{n}{2} + \tfrac{1}{2\sigma^2}\sum_{i=1}^{n}(x_i-\mu)^2 = \\ &= \tfrac{n}{2}\left(\tfrac{\hat{\sigma}^2}{\sigma^2} - 1 - \ln\left(\tfrac{\hat{\sigma}^2}{\sigma^2}\right)\right) + \tfrac{n}{2}\tfrac{(\overline{x}-\mu)^2}{\sigma^2}. \end{aligned} \quad (18)$$

Because for $x \in \mathbb{R}_+$ there is:

$$x - 1 - \ln x \geq 0, \quad (19)$$

it was received that:

$$l\left(\hat{\mu}, \hat{\sigma}^2; x_1, x_2, \ldots, x_n\right) - l\left(\mu, \sigma^2; x_1, x_2, \ldots, x_n\right) \geq 0, \quad (20)$$

so the determined point is actually the maximum of the function l (and therefore also of the function L). This means that the estimators of the distribution parameters searched for are as follows:

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} x_i = \overline{x}, \quad (21)$$

and:

$$\hat{\sigma}^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i-\overline{x})^2. \quad (22)$$

The maximum likelihood estimators for the parameters of all the above-mentioned distributions were determined in an analogous manner (x_0, λ for the exponential distribution, $x_0, \lambda,\ a$ for the gamma distribution, $x_0, \lambda,\ s$ for the log-normal distribution, and $x_0, \lambda,\ c$ for the Weibull distribution).

Given an empirical density function (using parameter estimators), one can determine the difference between its theoretical value derived from the determined distribution and the value from the experiment. The sum of the squares of these differences measures the quality of the fit: the larger it is, the more different the theoretical distribution is from the real data. Therefore, the distribution with the smallest sum of squares of differences was taken for further analysis. In particular, for each set of data, a distribution from a different family can be chosen.

Within the performed research, the mathematical model presented above was developed. This mathematical apparatus made it possible to calculate the reliability of entire furniture structures based on data on the reliability of individual connections and the type of structure connecting structural nodes.

The developed mathematical model was next used during the design and programming of the web application. The web application was created in the high-level language Python, which is characterized by an extensive package of standard libraries. In addition, additional objects and methods of this language were used to perform the necessary calculations: scipy.stats.expon (exponential distribution) [33], scipy.stats.gamma (gamma distribution) [34], scipy.stats.lognorm (log-normal distribution) [35], scipy.stats.weibull_min (Weibull distribution) [36], and scipy.stats.rv_continuous.fit (distribution matching) [37]. The program has a built-in database based on open-source solutions. It enables, among others, self-adding, deleting, and updating data. The results from the presented laboratory reliability investigations of furniture joints constitute the basis for the web application and the calculations.

The interface of the developed web application consists of two main modules. The first module allows users to present the designed furniture structures in the form of predefined views of 2D elements with the possibility of their parameterization. Importantly, it is a real-time, dynamic conversion of a 2D drawing. The second module is used to present data and the results of reliability calculations for both joints and the entire structure of the designed case furniture. In addition, the developed web application has several useful functionalities. It:

- Presents data in the form of tables and charts;
- Presents reliability diagrams and probability density functions (PDFs);
- Compares the reliability values for the variables chosen and indicates the best solution with the assumed probability;
- Saves a report on the performed calculations in the form of a * .pdf file;
- Exports data from tables in open formats * .csv, * .xml, * .json;
- Exports the generated charts to files with the * .png and * svg extensions.

The developed web application is available in two language versions: Polish and English.

The first module mentioned earlier is a “drawing” module. It consists of two blocks: the “settings” block and the “drawing” block. The first one contains options that allow the definition of the topology of the furniture construction and the design features of the furniture to be created. The second block allows the users to generate a two-dimensional presentation of the furniture in the front view. The “settings” block is divided into two parts. In the first, the user defines:

- Dimensions of the furniture (height, width, and depth), given in millimeters.
- Furniture properties, according to the scheme:
    1. Type of material (particleboard, MDF);
    2. Type of connector (dowel, confirmat, eccentric);
    3. Thickness of the element (16, 18, 22 mm);
- Number of connectors.

The second part of the settings allows the user to add additional furniture elements to the previously defined furniture construction. Among these settings, the user can add:

- Vertical partitions;
- Partition walls;
- Horizontal partitions.

When inserting additional elements, the web application indicates their dimensions by default, taking into account the previously defined thickness of elements and the overall dimensions of the furniture construction, also previously defined by the user.

Additionally, the web application allows the users to choose the reliability structure. If the option of the parallel structure is selected, it indicates that the reliability-increasing reserve has been applied by using an additional connector together with the already existing connector.

The second described module presents the results of the reliability calculations, namely, the reliability of the selected furniture joint, as well as the reliability of joints made of other materials and connectors, included in the program database. Thanks to this, the engineer can quickly assess the reliability of the designed furniture construction when using alternative materials or connectors. An important functionality of the developed web application is the ability to assess the failure-free service life of the furniture, which in practical terms can be used to determine the length of the warranty period. After making the calculations, the user can generate a full report containing the initial parameters of the furniture and the results obtained.

In order to present the full potential of the developed web application, in the third stage of the investigations, various variants of reliability structures that can be applied in furniture construction, meaning serial and parallel reliability structures, were verified.

In the analyzed example, in the first case, a serial reliability structure was adopted. Based on the conducted laboratory reliability tests and the developed mathematical apparatus implemented in the web application, it was possible to calculate the reliability of eccentric joints made of MDF of 18 mm (0.946). In the web application, as previously mentioned, the reliability of a whole case furniture construction depending on time can be determined as well. For example, after the assumed 24 months, the reliability of the whole analyzed case furniture construction consisting of eccentric joints made of 18 mm thick MDF when implementing serial reliability structure is 0.861. Furthermore, the same case-type furniture construction but consisting of eccentric joints made of the laminated three-layer particleboard of 18 mm was used for the reliability calculations. The reliability of the eccentric joint made of the laminated three-layer particleboard of 18 mm equaled 0.725. Whereas the reliability of the whole furniture structure after the assumed 24 months was calculated at the level of 0.281. This result confirms the earlier presented results of reliability calculations performed with the usage of Weibull++ specialized software.

For cognitive purposes, in the analyzed example, it was decided to change the serial structure of reliability to a parallel one. In this case, higher reliability results were obtained for the entire analyzed case furniture construction. The change of the reliability structure from serial to parallel caused an improvement in the reliability of the entire case furniture construction after the assumed 24 months period adopted in the analyzed example to 0.959. This is in line with literature sources stating that parallel structures improve the reliability of furniture [22]. In addition, for the same furniture construction made of the analyzed laminated three-layer particleboard, a significant improvement in the reliability of the whole piece of furniture is observed when the serial structure is changed for the parallel structure, as it raised to the level of 0.957.

4. Conclusions

The above-presented examples show the possibility of calculating the reliability of selected case furniture construction using a dedicated original web application. This tool can be useful for engineers and furniture designers to quickly assess the reliability of furniture constructions already at the initial design stage. It is of high importance as determining the reliability of furniture has a direct impact on the durability and safety of its use. Furthermore, the functionality of comparing the reliability of alternative connectors and materials in the web application allows the constructor to quickly evaluate them and, if necessary, decide to choose a solution that is more favorable in terms of the expected durability of the furniture. The generated detailed reports may constitute an important supplement to the product's technical documentation.

Additionally, the ability to compare the reliability results in the web application using the serial and parallel structure allows the constructor to make more informed design choices. Determining the failure-free operation time of the furniture construction, as a result of the web application operation, allows for a conscious extension of the warranty period offered and may contribute to the improvement of the company's competitiveness in the market. Additional laboratory tests are needed to enlarge the predefined web application database of furniture joints by adding data concerning other connectors, materials, and element thicknesses.

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