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Moisture swelling and shrinkage of pine wood versus susceptibility to robotic assembly of furniture elements

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Abstract: *Moisture swelling and shrinkage of pine wood and susceptibility to robotic assembly of furniture elements. Background and Objectives.* Processing technology, storage conditions and wood properties affect the actual dimensions of wooden elements. It was decided to experimentally check how the dimensions of samples, made of the selected wood species, will change under the influence of different storage conditions, typical for industrial environments. And especially how these changes will affect the susceptibility to assembly of upholstery frame rails that form a box joint. *Materials and Methods.* The tests were performed on three series of rails made of Scotch pine wood. Each tested series consisted of 12 elements. First, the five dimensions forming the box joint were measured. Then, each series was exposed to different conditions: in the industrial hall (air of RH = 29-48% and t = 16-24°C), in the compressor room (RH = 24-51%, t = 13-27°C) and outside in a covered shed (RH = 20-50%, t = 3-23°C). After 35 days the dimensions were measured again. *Results.* It was found that the average moisture content decreased and the dimensional deviations increased in the samples stored in the production hall and in the compressor room. In samples stored outside, the mean moisture content did not change, but the dimensional deviations increased significantly. *Discussion.* The storage of wooden elements increases the deviations from assigned dimensions. Exposure to repeated changes in moisture content and ambient temperature, even without changing the final moisture content of the elements, results in greater dimensional changes than storage under more stabilized conditions that reduce wood moisture content. *Conclusions.* The shrinkage and swelling of wood due to changes in its moisture content are not fully reversible, therefore, apart from maintaining the appropriate temperature and air humidity during storage, it is important to keep these conditions unchanged.

Keywords: Scots pine, dimensional stability, shrinkage, swelling, robotic assembly, engineering fit

INTRODUCTION

The actual dimensional deviations influence the clearance or press fits between two matching parts, i.e. they determine the susceptibility to assembly. Reduction of these deviations (reducing the width of the engineering tolerances) increases the susceptibility to assembly, but on the other hand, excessive reduction of the tolerance increases the manufacturing cost of products (Kien et al. 1979; Kulikov 1952; Porankiewicz 1989). For this reason, the tolerance should be set at the optimum level and its actual value should not change during production.

The causes of dimensional deviations of wood and wood composites products are inherent machining conditions, e.g. dynamic imbalance of the machine – tool – workpiece system, tool wear, machine tool setting errors, adverse effect of high temperature at the wood – cutting tool interface (Sydor et al. 2020). The causes of dimensional changes of products made of wood materials may also be the storage conditions, which cause deformation as a result of long-term creep under the load. In addition, the influence of changes in air temperature and humidity may also be the cause of dimensional deviations. Due to the affinity of wood and water, even a short-term contact of wood with water or long-term exposure to humid air results in changes in dimensions, i.e. swelling or shrinkage due to sorption (Kollmann and Côté 1968;

Noack et al. 1973; Skaar 1988; Wagenführ 2006). Water sorption phenomena in wood also depend on the type of wood (Ahmet et al. 1999), cambial age of wood (Simón et al. 2015), chemical composition of wood (Hernández 2007; Jankowska et al. 2016; Vahtikari et al. 2017).

Furniture elements, made of wood materials, are constantly subjected to cyclic and nonuniform changes in humidity adequate to the range and character of changes in the values of ambient air parameters (Spalt 1958; Wengert 1976; Gjerdrum 2008; Feilke et al. 2011; Majka et al. 2016; Jankowska 2018; Sydor et al. 2021). The moisture dimensional change of wood depends on the direction of sorption (adsorption or desorption). Due to the anisotropy of wood shrinkage and swelling, possible changes in the dimensions of elements cross-section (i.e. thickness and width) depend not only on changes in moisture content, but also on the orientation of annual growth. Moisture shrinkage or swelling (ΔN_w) Moisture shrinkage or swelling (Kollmann and Côté 1968):

$$\Delta N_w = 0.01 \cdot \Delta MC \cdot \beta \cdot N, \tag{1}$$

where: ΔMC – change in wood moisture content (%), β_w – directional coefficient of shrinkage/swelling (1/%), N – nominal dimension.

The technologies of mechanical processing of wood cause that the obtained elements are characterized by different orientation of annual increments on the cross-sectional area (tangential, radial, semi-radial grain patterns) (Langrish and Walker 1993), which significantly reduces the usefulness of equation (1) in the industrial practice. In addition, the suitability of a batch of lumber for the production of wood elements is determined by not exceeding the permissible moisture content spread (Welling 1996). Meanwhile, an unavoidable effect of the drying process of lumber used in the production of wood elements is the scattering of its moisture content. This means that the moisture content of part of the element batches is lower or higher than the expected range (Keylwerth 1969; Popper et al. 2009; Jankowska 2018).

Wood parts to be assembled may change significantly their dimensions due to the effect of ambient humidity. The change of humidity may hinder the assembly, which is still possible to perform, but requires additional technological operations, reducing the production efficiency. In extreme cases the assembly may be impossible. It is especially visible during the assembly performed by a robot, which has less possibility than a human to prevent abnormal situations resulting from the mismatch of assembled elements' dimensions (Laursen et al. 2018).

The aim of the described study was to experimentally determine the effect of storage conditions of wood elements in different environmental conditions on the variation of their dimensions in areas designed for joining (so-called box joints).

MATERIALS AND METHODS

The test samples were upholstery frame rails, the ends of which are intended to form box joints during assembly of four rails into the frame. The tested rails are shown in Fig. 1. All 36 samples are made of Scots pine wood with random grain patterns (tangential, radial and semiradial in various random combinations). In Figure 1, letters A through E indicate the tested critical assembly dimensions forming the box joints. Dimensions A and E were nominally 14.25 mm, dimensions B and D were 12.25 mm, and dimension C: 12.0 mm. Dimensions A, E, and C were internal (socket) dimensions, and dimensions B and D were external (tenon) dimensions.

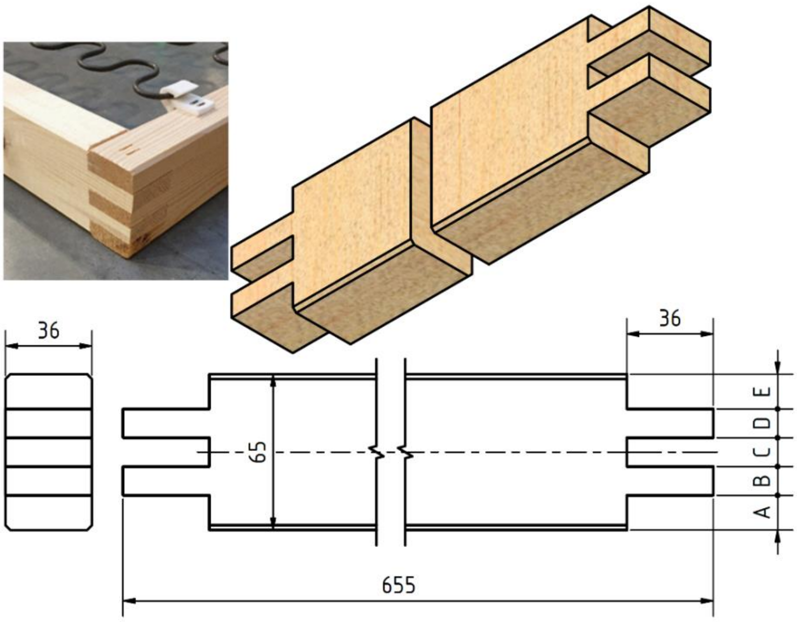

Figure 1. Test sample (rail of upholstery frame)

Samples were divided into three series of 12 items each (X, Y and Z designations), then the dimensions from A to E and the relative moisture content of the samples were measured. The next step was to expose each series of samples to different environmental conditions (seasoning). Series X was stored in the production hall, series Y – in the compressor room, and series Z was exposed to ambient conditions by placing outdoor but in a covered open shed in European temperate climate (April 2021, Leszno, Poland). These three different storage conditions corresponded to the typical industrial storage conditions of the furniture components. The seasoning lasted for 5 weeks (35 days), from 31.03.2021 to 5.05.2021. The variable environmental conditions affecting the tested series of specimens are shown in Fig. 2.

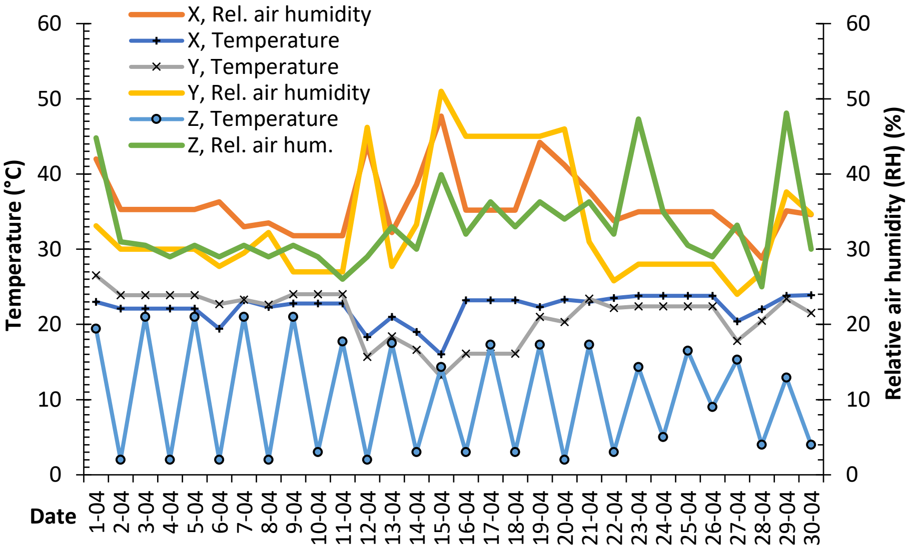

Figure 2. Environmental conditions affecting the samples (X – production hall, Y – compressor room, Z – outdoor)

The series X was exposed to a temperature range of 16-24° (mean 22°C) and an relative air humidity range of 29-48% (mean 36% RH); serie Y was exposed to a temperature range of 13-27°C (mean 21°C) and RH of 24-51% (mean 33%). The samples of the Z series were stored in the temperature from 2°C at night to 23°C during the day (mean 12°C) and RH of 20-49% (mean 32%). After the end of seasoning, the dimensions A, B, C, D and E and the moisture content of all samples were measured again.

RESULTS AND DISCUSSION

The average measured dimensions of the samples before exposing to different environmental conditions are shown in Table 1.

Table 1. Average dimensions of samples before exposing to different environmental conditions

Dimension	Nominal dimension	Mean for series X	Mean for series Y	Mean for series Z
A	14.25	14.30 (±0.06)	14.32 (±0.09)	14.15 (±0.09)
B	12.25	12.30 (±0.03)	12.24 (±0.04)	12.37 (±0.04)
C	12.00	11.73 (±0.02)	11.72 (±0.02)	11.69 (±0.02)
D	12.25	12.29 (±0.05)	12.31 (±0.02)	12.37 (±0.04)
E	14.25	14.22 (±0.09)	14.25 (±0.07)	14.10 (±0.07)

In parentheses, error according to Student's t-distribution: $n = 12$ ($k = 11$), $\alpha = 0.05$, $T = 2.03$

The differences between the average measured dimensions and the nominal dimensions before exposing to different environmental conditions (before seasoning) are shown in Fig. 3.

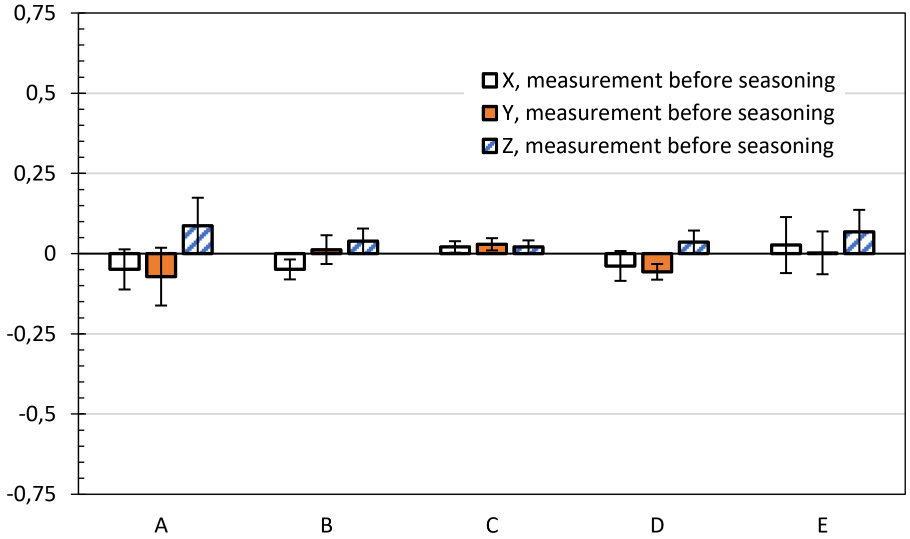

Figure 3. Difference between the average measured dimensions and nominal dimensions for series X, Y, Z (before seasoning)

The average moisture contents of the tested sample series are shown in Table 2.

Table 2. Initial moisture content (*MC*) of test samples (before seasoning)

Serie	MC [%]
X	10.18 (1.23)
Y	9.69 (0.71)
Z	9.43 (0.71)

Mean value for $n = 12$, standard deviation (SD) in parentheses

The average measured dimensions of samples after seasoning are shown in Table 3.

Table 3. Average dimensions of samples after seasoning

Dimension	Nominal dimension	Mean for series X	Mean for series Y	Mean for series Z
A	14.25	14.50 ±0.26	14.43 ±0.14	14.51 ±0.11
B	12.25	12.19 ±0.05	12.22 ±0.06	**12.46 ±0.05**
C	12.00	11.90 ±0.05	11.66 ±0.05	12.02 ±0.07
D	12.25	12.27 ±0.03	12.25 ±0.02	12.41 ±0.04
E	14.25	14.32 ±0.09	14.31 ±0,10	14.51 ±0.13

Differences between the mean value of measured dimensions and nominal dimensions after seasoning are shown in Figure 4.

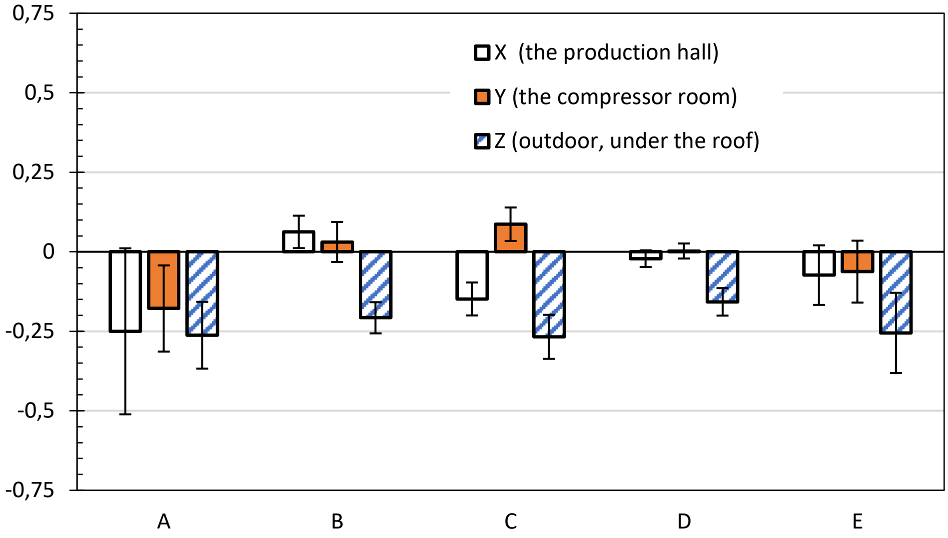

Figure 4. Difference between the mean value of measured dimensions and the nominal dimension for series X, Y, Z (after seasoning)

By comparing Fig. 2 and Fig. 3 it can be concluded that the dimensions have changed. The internal dimensions (A, C and E) of three sample series have increased (except dimension C of the series located in the compressor room, Y). While the external dimensions (B and D) decreased for the series seasoned in the production hall (X) and in the compressor room (Y), they increased for the series stored outside (Z).

The average moisture content of the tested sample series after seasoning are presented in Table 4. These moisture contents decreased significantly for series X and Y (they were on the limit of the moisture meter measuring range). Series Z, on the other hand, had a mean moisture content close to the initial moisture content, but the individual elements moisture contents of this series were highly differentiated (increased standard deviation).

Table 4. End moisture content (*MC*) of Scots pine after seasoning

Serie	MC (%)
X	< 4 (n.d.)
Y	ca. 6 (n.d.)
Z	8.73 (2.47)

Mean value for *n* = 12, standard deviation (SD) in parentheses

Moisture-related dimensional changes of industrially manufactured wood products have been the subject of many papers (Kulikov 1968; Kruś 1997). The aim of these studies was to measure the moisture content coefficients of dimensional changes, the knowledge of which is essential for technological product design, oriented to assembly. It was established that these changes have an approximately linear nature in the range of moisture content changes (Δw) from 0 to 14% – and according to some papers up to 20% – are to some extent reversible and are characterized by high anisotropy in relation to the anatomical directions of wood and depend on the wood species (Keylwerth 1969; Popper et al. 2009; Jankowska 2018).

Kulikov (1968) analyzed the moisture content distributions on cross-sections of element batches made of kiln-dried timber to mate the elements in a way that would later reduce unfavorable clearances in joints. The primary difficulty is that the basic anatomical direction rarely occurs in solid wood products. The orientation of annual increments on the cross-section of wood/lamellas/lumber material elements (tangential materials, radial materials) is determined by the previously applied technology of mechanical wood processing (Langrish and Walker 1993). In industrial practice, anatomically "unidirectional" elements are not commonly found, and the same is true here. The tested samples have different, rather random "tangent-radius" fiber orientations.

The rules for tolerating the designed dimensions of products made of selected species of wood and wood-based materials with MC corresponding to low, intermediate and high air RH, taking into account the shrinkage/swelling anisotropy, are included in DIN 68100. The current requirements in this standard are not harmonized with the GPS Geometrical Product Specification standard system (ISO 14638 2015) published completely in 2011, which hinders its use in industry.

One of the two box joint elements described in this paper was tested. Both elements have an applied technological assembly clearance of 0.5 mm. Assuming that the second joint element retains its nominal dimensions, the results obtained indicate that the storage conditions (i.e. changes in the element's moisture content and the resulting changes in its dimensions) significantly influence the type of fit of the mounting pairs (clearance or interference). Analyzing Table 1 and Fig. 3 as well as Table 3 and Fig. 4 it can be concluded that the structural clearance fit (with the mentioned clearance of 0.5 mm), in the case of rails stored in external conditions (Z series), turns into a press fit. This is caused by the outer dimension B, which is 95% certain to exceed 12.5 mm and make the robotic assembly less or more difficult (the montage problems are potential, whether the problems arise should be tested in practice, as the robot has some capabilities to overcome the resistance caused by excessive fit – no clearance). The dimension B is marked in Table 3.

CONCLUSIONS

The experimental results indicate that:

- all exposure of wooden elements to different and variable air humidity increases deviation of actual dimensions from assigned dimensions;
- exposure of elements to big changes in air relative humidity and temperature, even without changing wood final moisture content, causes greater dimensional changes than storing elements in a more stabilized environment, resulting in a reduction in their moisture content.

The shrinkage and swelling of wood due to changes in its moisture content are not fully reversible, and therefore even elements made of pine wood with unchanged humidity relative to the initial humidity, but exposed to multiple changes in humidity, can significantly change their dimensions. The explanations for the results of our study are the multidirectional and not completely irreversible moisture deformation of wood. They occur in different anatomical directions with different intensity and are also different in absolute value when decreasing and increasing moisture content. The novelty of our research is the indication that in addition to maintaining the appropriate temperature and air humidity during storage, it is important to keep these conditions unchanged.

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Streszczenie: *Pęcznienie i kurczenie się drewna sosnowego a podatność na zrobotyzowany montaż elementów mebli. Wprowadzenie.* Technologia obróbki, warunki przechowywania i właściwości drewna wpływają na rzeczywiste wymiary elementów drewnianych. Postanowiono eksperymentalnie sprawdzić jak zmienią się wymiary próbek, wykonanych z wybranego gatunku drewna pod wpływem różnych warunków przechowywania, typowych dla środowisk przemysłowych. A zwłaszcza jak te zmiany wpłyną na podatność na zrobotyzowany montaż ramiaków ram tapicerskich, tworzących połączenie wielowpustowe. *Materiały i metody.* Badania przeprowadzono na trzech seriach ramiaków z drewna sosny zwyczajnej. Każda testowana seria składała się z 12 elementów. Najpierw zmierzono pięć wymiarów tworzących połączenie wpustowe. Następnie każda seria została wystawiona na inne warunki: przechowywanie w hali przemysłowej (powietrze o wilgotności względnej 29-48% i temperaturze 16-24°C), w sprężarkowni (RH = 24-51%, t = 13-27 °C) i na zewnątrz w zadaszonej wiacie (RH =

20-50%, t = 3-23°C). Po 35 dniach ponownie zmierzono te same wymiary ramiaków. *Wyniki.* Stwierdzono zmniejszenie średniej wilgotności oraz niewielkie zwiększenie odchyłek wymiarowych w próbkach przechowywanych w hali produkcyjnej i w sprężarkowni. W próbkach przechowywanych na zewnątrz średnia wilgotność nie zmieniła się, ale znacznie zwiększyły się odchyłki wymiarowe. *Dyskusja.* W analizowanych warunkach składowanie elementów drewnianych w każdym przypadku zwiększa odchyłki od wymiarów nominalnych. Narażenie na powtarzające się zmiany wilgotności i temperatury otoczenia, nawet bez zmiany końcowej wilgotności elementów, powoduje większe zmiany wymiarów niż przechowywanie w bardziej ustabilizowanych warunkach, które zmniejszają wilgotność drewna. *Wnioski.* Skurcz i pęcznienie drewna pod wpływem zmian jego wilgotności nie są w pełni odwracalne, dlatego oprócz zapewnienia właściwych temperatury i wilgotności powietrza przy przechowywaniu, ważne jest zachowanie niezmienności tych warunków.

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