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OPTIMISATION OF A SOFA FRAME IN THE INTEGRATED CAD-CAE ENVIRONMENT

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ABSTRACT

Majority of manufacturers of upholstered furniture design construction frames on the basis of craftsman's intuition and imitation rather than on the basis of engineer practice. The objective of this study was to present a method for the dimension sub-optimisation of cross-section diameters of a sofa frame construction and to demonstrate the need for virtual prototyping of upholstered furniture in an integrated computer aided design (CAD) and computer aided engineering (CAE) environments.
The concept of the performed investigations assumed the need to select sub-optimal dimensions of cross sections and thicknesses of the construction constituent elements of a two-person sofa frame on the basis of numerical calculations of developed solid models. However, undertaking appropriate steps towards the planned construction sub-optimisation required carrying out strength tests in order to verify the suitability of models developed in the environment of the finite element method. Corroboration of the satisfactory quality of the results of these calculations allowed proposing cross sections of reduced dimensions and next to manufacture an experimental construction of sufficient rigidity and strength in industrial applications.
It was demonstrated on the basis of the performed experiments that the proposed dimensions of the main construction elements put forward following the performed sub-optimisation decreased beech wood consumption by 36% and that of particle board – by 25%. Reduced dimensions of the most important construction elements did not result in a significant decrease of the stiffness and strength of the sofa frame.

Key words: furniture, optimisation, numerical analysis, CAD, CAE

INTRODUCTION

Designing of upholstered furniture, for majority of manufacturers, is confined to the employment of an architect who is expected to equip the future product in an innovative aesthetic form and appropriate practical functions and to a craftsman's execution of the construction frame based on intuition and imitation of competitors. As a rule, due to lack of engineering know-how, manufacturers do not optimise dimensions of the component elements of the construction for fear of the inappropriate adjustment of the strength of the designed piece of furniture to utilisation applications. First attempts of numeric optimisation of construction frames of upholstered furniture were undertaken by Smardzewski [4]. Wang et al. [5,6,7,8,9] pointed to possibilities of utilisation of OSB boards in production of frame construction elements of upholstered furniture as a substitute material for widely employed particle boards. However, one of the preconditions of application of OSB boards is the necessity of joining these elements with metal plates or gusset plates and glue.

Dai and Zhang [1] and Erdil et al. [2] presented simple structural analyses which are possible to apply in the production engineering of frames for sofas manufactured from OSB boards, plywood or soft wood. According to these researchers, the proposed analytical methods are intended to rationalise dimensioning of frame construction elements of upholstered furniture. However, the above researchers, utilising simple instruments of strength analysis of simple beams determinable statically, base their considerations on considerable approximations and these solutions are not precise. It is worth stressing that construction frames of upholstered furniture constitute systems which are internally statically repeatedly undeterminable. Therefore, for the above-mentioned systems, displacements and values of internal forces also depend on the kind of the applied materials, hence on values of their linear and shape elasticity moduli. Kasal [3] carried out numerical calculations for different frame constructions of sofas as special systems statically internally undeterminable. However, in his calculations he adopted a simplifying assumption that the employed materials have features of isotropic bodies. The application of such simplifications in analyses of constructions manufactured for orthotropic materials is unjustified at present. Majority of CAD programs widely employed in design departments of furniture factories are equipped in integrated CAE modules allowing fairly intuitive numerical calculations of stiffness and strength of solid models under design.

The objective of this study was to sub-optimise cross-section diameters of a sofa frame construction and to demonstrate the necessity for virtual prototyping of upholstered furniture constructions in an integrated CAD-CAE environment.

MATERIAL AND METHODS

Investigations were carried out on a two-person sofa frame of natural size (Fig. 1) manufactured on a large scale in accordance with standard procedures by one of the largest producers of upholstered furniture in Poland. Prior to optimisation (model A), the frame was made up of side elements manufactured from a particle board, a seat and backrest made of an HDF board and beam elements from pine and beech wood (Fig. 2).

Fig. 1. Natural size sofa frame

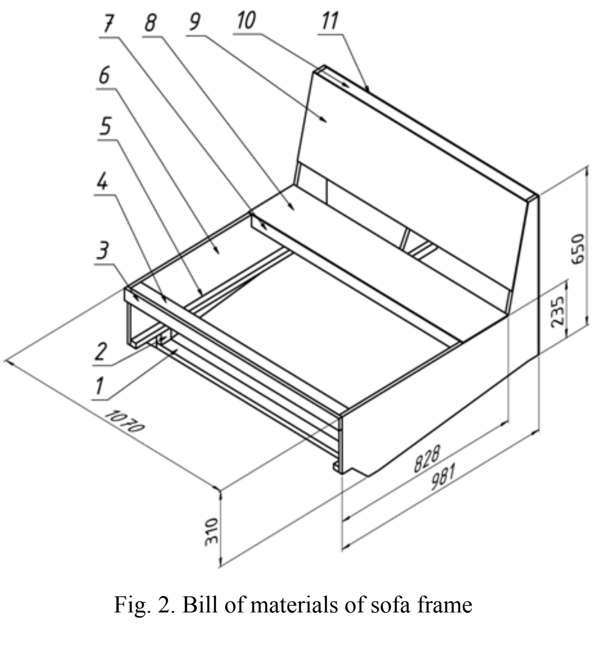


Fig. 2. Bill of materials of sofa frame

All construction elements were joined with one another by polyvinyl acetate glue applied to adjacent surfaces and steel clips fixed at the side of the element of smaller thickness. The applied steel stitches measured 8 x 26 mm and were distributed randomly in the amount of 4 at each transverse cross section of a longitudinal crosspiece and every 100 mm along the symmetry axis of slats fixed to board elements. The purpose of glue application was to stiffen the joints and improve the load carrying capacity of steel clips. The choice of polyvinyl acetate glue resulted from industrial applications which appreciates its ease of simple application when cold as well as rapid hardening and appropriate fire resistance. The employed glue was characterised by density of about 1.05 g/cm^3, viscosity of 170-195 cps and acid reaction (pH = 5).

Model A selected for laboratory experiments was supported and loaded statically in accordance with the scheme shown in Fig. 3 and then, in the sequence also indicated in this figure, it was loaded with concentrated forces of values P_1,P_2,P_4 = 800N and P_3 = 500N. The adopted load scheme differs from commonly accepted recommendations found in European and American standards. However, the adopted solution aimed at causing in the examined construction strains and stresses which occur in extreme applications, sometimes incompatible with its function. The value of the adopted load corresponded to the weight of a man of European population of the 50th percentile exerting a suitable pressure on individual crosspieces of the seat, backrest and sides. Displacements of the points of application of individual forces along appropriate directions of their action were also investigated in the course of the performed tests. Strength tests were carried out in the Laboratory of Furniture Investigations and Attestation at the Department of Furniture Design of the Poznań University of Life Sciences using for this purpose a testing machine which consists of pneumatic actuators and a system of automatic controls. The accuracy of the applied loads amounted to ±1N and that of displacement measurements ±0.05 mm.

Normal strains were determined in selected points of the construction with points T_1 and T_2 placed on the bottom surface of beams designated in Fig. 2 as points 4 and 7, respectively, whereas points T_3 and T_4 were placed on the location symmetrical to the side designated on Fig. 2 with number 6 (Fig. 3).

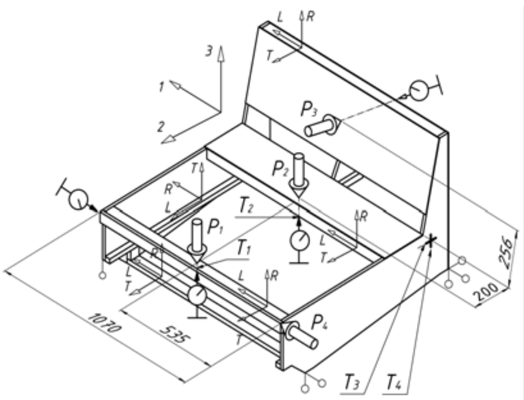


Fig. 3. Loading diagram of sofa frame

Strain measurements were taken by gluing strain gauges of R_g = 120Ω and of constant GF = 2.15 at indicated points T_1,T_2,T_3,T_4. The strain gauges were connected to Wheatson's bridge type SCXI 1314 of National Instruments Company using leads of R_L = 0.2Ω resistance. In the course of the loading cycle with P_1,P_2,P_3,P_4 forces, changes in the measuring voltage V_{CH} generated by the deformation of the strain gauge were recorded. The bridge was configured as a quarter-bridge (Fig. 4).
The voltage coefficient was "Eq. (1).",

$$V_r\big|_{P_1,P_2,P_3,P_4} = \frac{\left(V_{CH\,\max} - V_{CH\,\min}\right)\big|_{P_1,P_2,P_3,P_4}}{V_{EX}} \tag{1}$$

While recording changes in the quarter-bridge arrangement, ε strains generated with P1,P2,P3,P4 forces were calculated "Eq. (2).",:

$$\varepsilon\big|_{P_1,P_2,P_3,P_4} = \frac{-4V_r\big|_{P_1,P_2,P_3,P_4}}{GF(1+2V_r\big|_{P_1,P_2,P_3,P_4})} \times \left(1+\frac{R_L}{R_g}\right) \tag{2}$$

and then normal σ stresses were determined from the dependence "Eq. (3).":

$$\sigma = \varepsilon \cdot E \tag{3}$$

where: E – module of elasticity of the material on which the strain-gauge was glued.

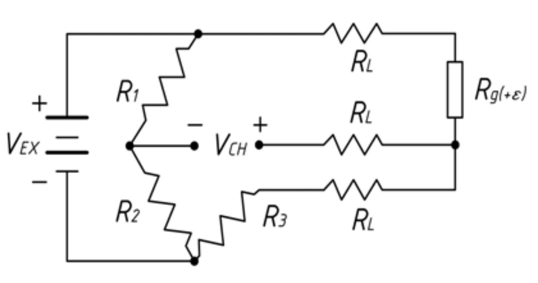


Fig.4. A quarter-bridge arrangement: R_1, R_2 – compensatory resistors in a half-bridge arrangement, R_3 – dummy gauge in a half-bridge arrangement, R_4 – active strain-gauge element measuring positive strains (+ε), V_{EX} – excitation voltage 1V, R_L – lead resistance, V_{CH} – measured voltage 4V

Before laboratory investigations, real frame models of A and C sofas were air-conditioned in a special laboratory compartment for the period of 2 months in conditions of air temperature of 20±1°C and air relative humidity of 65±5%.

For the selected A model of the sofa frame, numerical calculations were performed using for this purpose Algor software employing the finite element method algorithm. When preparing the 3D geometric model of the sofa frame for numerical calculations, the authors utilised the solid model recorded by designers in an ACIS format of the CAD parametric system. When copying the solid model into the Algor system pre-processor, a network made up of cuboid 20-node finite elements of 'brick' type was plotted onto it (Fig. 5). In places where elements of different thicknesses and cross sections were connected as well as in places in which strain gauges were glued on the real object, networks were concentrated in such a way as to achieve the necessary consistency of the construction and an accurate picture of the state of strains and stresses.

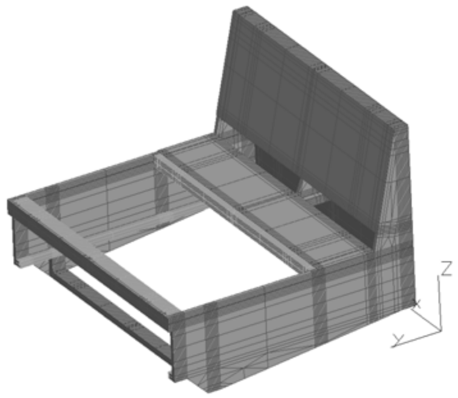


Fig. 5. Finite elements network model

Connections between elements were of elastic nature and reflected mechanical properties of the materials found in the place of joint.

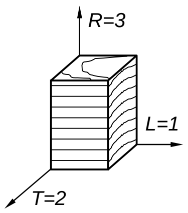
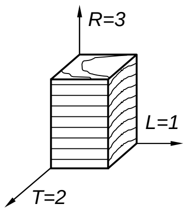
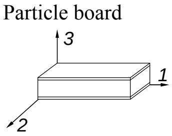
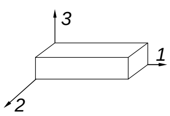
Bearing in mind the application of several types of materials of different mechanical properties and different orientation within the space of the model, separate material groups were identified in the Algor system. The number of these groups corresponded to the number of material combinations and their mutual orientation with regard to the global and local coordinate systems (Fig. 3). Individual material groups written down on separate layers were assigned appropriate material data which characterised their strength and elastic properties of: pine wood, beech wood, particle board and HDF. Since the quality of calculation results depends on the quality of the data fed in, the authors decided to carry out detailed basic investigations the aim of which was to determine elastic properties of all materials as orthotropic solids by determining the elements of the matrix "Eq. (4).",:

$$\begin{bmatrix} \frac{1}{E_L} & -\upsilon_{TL}\frac{1}{E_T} & -\upsilon_{RL}\frac{1}{E_R} & 0 & 0 & 0 \\ -\upsilon_{LT}\frac{1}{E_L} & \frac{1}{E_T} & -\upsilon_{RT}\frac{1}{E_R} & 0 & 0 & 0 \\ -\upsilon_{LR}\frac{1}{E_L} & -\upsilon_{TR}\frac{1}{E_T} & \frac{1}{E_R} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{LT}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{LR}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{TR}} \end{bmatrix} \tag{4}$$

with L = 1, T = 2 and R = 3 for the particle board,
where: E_L, E_R, E_T – linear elasticity moduli in longitudinal, radial and tangential directions, respectively, G_{LR}, G_{LT}, G_{TR} – rigidity modulus in anatomical (or technological) directions: longitudinal-radial, longitudinal-tangential and tangential-radial, ν_{LR}, ν_{LT}, ν_{RT}, ν_{TR}, ν_{RL}, ν_{TL} –Poisson's coefficients in respective anatomical (or technological) directions: longitudinal-radial, longitudinal-tangential, radial-tangential, tangential-radial, radial-longitudinal and tangential-longitudinal.

The value of the appropriate matrix elements of elasticity for wood was determined on a ZWICK 1445 testing machine using strain gauge measurements. Experiments were carried out in a single-axis compression test of 6 types of cuboid samples of 30 x 30 x 60 mm dimensions of 60 samples for each wood species and applying pressure with the velocity of 2 mm/min. The elasticity properties of the employed particle board and HDF board were determined in a bending test performed on the same testing machine using strain gauge measurements. The samples of experimental boards were of the following dimensions: particle board – 16 x 50 x 350mm and HDF – 3.2x50x105mm. Each of these materials was represented by 10 samples with a parallel course of direction of the board formation in relation to the longer side of the crosspiece and 10 samples with a perpendicular course of direction of the board formation in relation to the longer side of the crosspiece. Results of these investigations are collated in Table 1.

Table 1. Elasticity properties of materials

Material	Properties	Average	Standard deviation	Coefficient of variation [%]
Pine 	E_L [MPa]	10320.00	866.79	0.084
	E_R [MPa]	1107.10	239.44	0.216
	E_T [MPa]	493.27	117.21	0.238
	G_{LR} [MPa]	1287.85	278.92	0.217
	G_{LT} [MPa]	702.87	143.45	0.204
	ν_{LR}	0.447	0.092	0.205
	ν_{LT}	0.467	0.098	0.211
	ν_{RL}	0.035	0.007	0.206
	ν_{RT}	0.536	0.113	0.210
	ν_{TL}	0.031	0.006	0.201
	ν_{TR}	0.358	0.073	0.205
Beech 	E_L [MPa]	14346.7	2742.41	0.191
	E_R [MPa]	1455.9	256.23	0.176
	E_T [MPa]	743.6	167.43	0.225
	G_{LR} [MPa]	1472.34	293.92	0.200
	G_{LT} [MPa]	844.82	145.62	0.172
	ν_{LR}	0.443	0.117	0.264
	ν_{LT}	0.426	0.072	0.169
	ν_{RL}	0.044	0.009	0.205
	ν_{RT}	0.637	0.104	0.163
	ν_{TL}	0.056	0.010	0.179
	ν_{TR}	0.382	0.080	0.209
Particle board 	E_1 [MPa]	3080.00	592.45	0.192
	E_2 [MPa]	2530.00	436.00	0.172
	G_{12} [MPa]	794.00	128.00	0.161
	ν_{12}	0.207	0.032	0.155
	ν_{21}	0.282	0.028	0.099
HDF 	E_1 [MPa]	4000.00	642.52	0.161
	E_2 [MPa]	3850.00	489.00	0.127
	G_{12} [MPa]	1509.61	167.00	0.111
	ν_{12}	0.3	0.044	0.147
	ν_{21}	0.3	0.029	0.097

The static bending strength of individual materials was determined in a three-point bending test of beams of appropriate lengths. In the case of particle boards and HDF, the same samples used to determine elastic properties were employed, whereas for pine and beech wood – 10 beams each of 20 x 20 x 300 mm dimensions were prepared. Results of these experiments are presented in Table 2.

Table 2. Mechanical properties of materials

Material	Average [MPa]	Standard deviation [MPa]	Coefficient of variation [%]
Pine	79.,00	6.58	8.23
Beech	127.60	6.15	4.82
Particle board	15.00	0.79	5.27
HDF	17.46	1.14	6.52

All samples for material investigations were collected directly from the production hall of the company mentioned earlier.

The final stage in the development of the numerical model of the calculated construction involved the adoption of support conditions and loads for the examined sofa frame. For this purpose, the scheme shown in Fig. 3 was employed.

Table 3. Dimensions of sofa frame elements

No	Element	Material	Model A			Model B			Model C		
			Dimensions [mm]								
1	Bottom rail	Pine	22.0	50.0	1038.0	22.0	50.0	1038.0	22.0	50.0	1046.0
2	Block	Pine	–	–	–	22.0	50.0	53.0	22.0	50.0	53.0
3	Front rail	Particie board	16.0	50.0	1070.0	16.0	50.0	1070.0	12.0	50.0	1070.0
4	Stretcher A	Beech	50.0	50.0	1038.0	50.0	50.0	1038.0	35.0	45.0	1046.0
5	Side slat	Pine	22.0	27.0	928.0	22.0	27.0	928.0	22.0	27.0	928.0
6	Side	Particie board	16.0	–	–	16.0	–	–	12.0	–	–
7	Stretcher B	Beech	50.0	50.0	1038.0	50.0	50.0	1038.0	35.0	45.0	1046.0
8	Seat board	HDF	3.2	225.0	1070.0	3.2	225.0	1070.0	3.2	225.0	1070.0
9	Back board	HDF	3.2	335.0	1070.0	3.2	335.0	1070.0	3.2	335.0	1070.0
10	Back rail	Pine	22.0	50.0	1038.0	22.0	50.0	1038.0	22.0	50.0	1046.0
11	Mantle	HDF	3.2	650.0	1070.0	3.2	650.0	1070.0	3.2	650.0	1070.0

Dimensions of cross sections of the construction elements of the sofa frame are collated in Table 3 taking into account three models of its execution. Elements marked with bold frames are those whose measurements underwent sub-optimisation on the basis of the results of numerical calculations and laboratory experiments.

RESULTS AND DISCUSSION

In the course of the first stage, the authors carried out numerical calculations for the A model of the sofa frame which were followed by laboratory tests; the results of calculations and measurements are presented in Table 4. Comparing measured and calculated values of deflections of the construction elements, it can be observed that differences range from 4.1% to 12.2%. On the other hand, differences between the laboratory-determined and numerically-calculated strains in selected construction points range from 1.5% to 11.3%. Such differences can be treated as acceptable and they confirm high quality of the numerical model elaborated with the assistance of the finite element method. In addition, the performed measurements of displacements of points to which loads were applied as well as the results of numerical calculations revealed that the majority of individual construction elements of the sofa underwent either bending (Fig. 6a,b,c) or torsion (Fig. 6d). Bearing this in mind, during the sub-optimisation process, the authors decided to take this information into account and proposed solutions aiming at reducing cross sections of selected main construction elements maintaining, at the same time, sufficient safety of the examined piece of furniture, its rigidity and strength.

Table 4. Displacement and stresses in selected point of sofa frame

Loading	Point of measuring	Model A				Model B		Model C			
		laboratory measure		numerical calculations		numerical calculations		numerical calculations		laboratory measure	
		deflection	stress	deflection	stress	deflection	stress	deflection	stress	deflection	stress
		[mm]	[MPa]	[mm]	[MPa]	[mm]	[MPa]	[mm]	[MPa]	[mm]	[MPa]
P1	T1	4.35	3.72	4.02	3.87	3.88	3.81	5.61	5.13	5.90	5.25
P2	T2	3.85	10.38	3.38	10.22	3.33	10.14	4.77	14.11	4.80	14.25
P3	T3 T4	0.75	0.20 0.71	0.55	0.19 0.63	0.54	0.19 0.61	0.57	0.26 0.71	0.70	0.30 0.70
P4	–	5.85	–	5.61	9.64	4.01	10.57	6.66	9.32	6.85	9.20

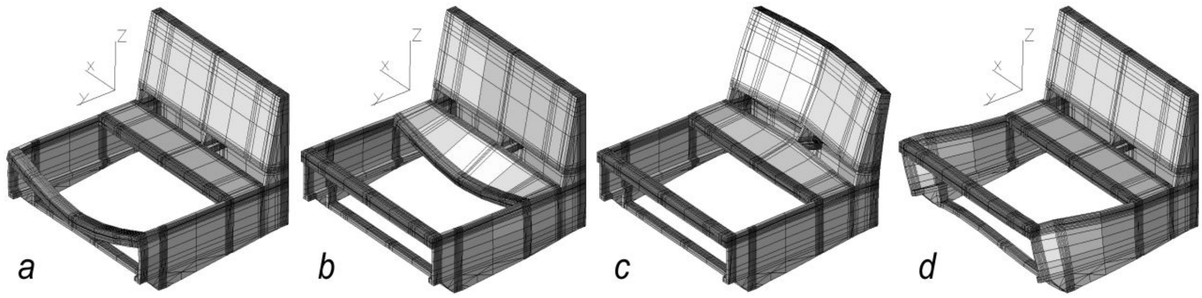


Fig. 6. Diagram of deformation of sofa frame: a,b,c – bending, d – torsion

On the basis of the above data a new, numerical B model of the sofa frame was developed which differed from the A model in that it employed strengthening blocks measuring 22 x 50 x 53mm made from pine wood which were fixed using polyvinyl acetate glue and steel clips to the side of the frame just over the beams and transverse slats (Fig. 7). The objective of numerical calculations for this solution was to ascertain changes in the construction stiffness as well as in the strain distribution generated by used loads. In addition, this was to facilitate the choice of the method of construction optimisation: either by changes in the dimensions of constituent elements or by the change of the applied materials. Results of these calculations are presented in Table 4.

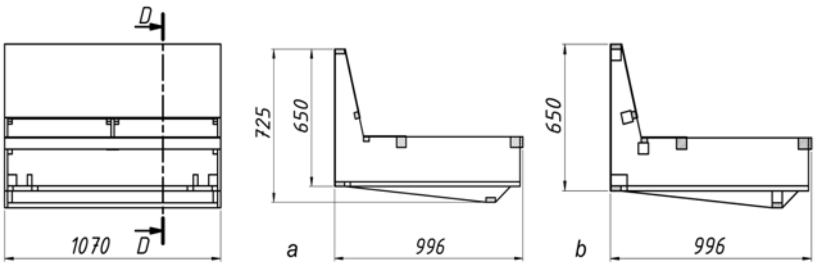


Fig. 7. Vertical cross section of sofa frame (dimensions in mm): a – A model, b – B model

It was demonstrated on the basis of these results that, in comparison with the results of the numerical calculations prepared for the A model, deflections of elements in model B were, on average, by 8.8% smaller. In addition, the application of strengthening blocks did not cause significant changes (on average, by 1%) in the strength of the examined construction elements. Therefore, in further experiments, the authors decided to follow the direction of construction suboptimisation involving the application of the same materials and selection of new cross sections and thicknesses of the main construction elements.

It was, therefore, proposed to chose new 35 x 45mm cross section dimensions of elements designated in Fig. 2 as 4 and 7 as well as a smaller (by 12 mm) side thickness of the sofa frame, designated in Figure 3 as 6 (Table 3). The remaining construction assumptions for this model remained identical as in model B.

It is clear from the comparison of the numerical calculations presented in Table 4 for models B and C that deflections of the construction elements in model C were by about 2.5 mm (i.e. 40%) greater than the deflections of the same elements in model B. In addition, also values of normal strains in the selected points of model C were on average by 1.33 MPa higher (i.e. by 28.8%) in relation to the corresponding values in model B. Therefore, the obtained results of numerical calculations were considered as satisfactory and a 1:1 scale real model of the C sofa frame was made. The construction was then subjected to identical strength tests as model A and the obtained values of deflections and strains are collated in Table 4. It is evident from the presented data that deflections determined numerically, on average,

showed by 7.8% smaller values (0.3 mm) in comparison with the values of deflections measured in laboratory tests. On the other hand, the difference in strain values, on average, amounted to 3.2% (0.14 MPa).
Hence, it can be said that laboratory tests corroborated the structure appropriateness of the numerical model as well as their effectiveness for rapid, virtual construction sub-optimisation of wooden upholstered furniture. Moreover, it should be emphasised that the proposed smaller dimensions of the main construction component elements did not reduce the operational safety of the sofa frame. Bearing in mind the fact that the maximal normal strains in beech wood elements caused by bending reached the value of 15 MPa and that the strength of beech wood used to manufacture the experimental construction was at the level of 127.6 MPa, the safety coefficient for these elements was at the level of n = 8.5, while for the particle board used for sides this coefficient was 1.6. Therefore, it can be said with absolute certainty that the new, sub-optimal construction of the sofa frame prepared for the furniture company is sufficiently strong and safe for users.
An additional advantage of the performed construction sub-optimisation is a considerable reduction in the volume of the employed materials (Table 5). In the case of beech wood and particle board, material savings amounted to: 36.51% and 25%, respectively.

Table 5. Capacity of materials in sofa frame

	Volume [m^3]		
Model	pine	beech	particie board
A	0.000000	0.005190	0.002072
B	0.000058	0.005190	0.002072
C	0.000058	0.003295	0.001554
material savings [%]	–	36.51	25.00

CONCLUSIONS

Investigations presented in this study confirmed that the designed frame constructions of upholstered furniture are manufactured on the basis of craftsman's intuition and imitation rather than on the basis of engineering practice using appropriate informatics tools assisting the designing process. This leads to considerable material overinvestment and, consequently, to increased technical costs of production of upholstered furniture. Therefore, engineers and furniture designers should be encouraged that when using computer aided design (CAD), at present integrated with computer aided engineering (CAE) systems, (especially, with modules allowing calculations with the assistance of the finite element method) they should also take advantage of numerical calculations of these constructions and, on the basis of the results of such calculations, make appropriate decisions concerning optimisation of the proposed construction solutions. The performed experiments and obtained results allow drawing the following conclusions:

1. Numerical calculations provide correct results only on condition that data about elastic properties of the applied orthotropic materials determined on the basis of laboratory investigations are prepared.
2. The proposed new dimensions of the main construction elements reduced the consumption of beech wood by 36% and that of particle board – by 25%.
3. Reduction of dimensions of the main construction elements did not lead to significant, from the point of view of frame construction, deterioration of its rigidity and strength.
4. The new frame construction of the sofa was implemented into production.

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