UNIVERSITY OF WEST HUNGARY

THESES OF THE DOCTORAL (PH.D.) DISSERTATION

DEVELOPMENT OF A NEW VENEER BASED COMPOSITE USING THE EXPERIMENTAL DESIGN METHOD

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1. Objective of the research

Wood as a renewable resource is an integral part of our life and appears in very different forms in the surrounding environment. The world is hardly imaginable without forests and the man's milieu without wooden objects. Therefore the question if needs can be covered with wood, where can we find and in which form these materials is justified on the edge of the third millennium. The response is very important for the wood industry too, because it will determine the direction of the developments.

Quantitative and qualitative analysis of the available wood-based resources shows that sufficient base material will be accessible in the future, but the quality, size and composition face significant changes. This will change the conversion technologies also. Hence the research and development activities must concentrate on the optimal and efficient utilization of the altered wood material, on the elaboration of flexible and environment-friendly technologies and on the recycling of the production's residues.

Another possibility to save the wooden resources lies in producing robust and durable products with high quality. Nowadays quality and reliability play an important role in the customer's choice ergo continuous development of product and process quality is key-question for customer's satisfaction attainment and economic success as a consequence. During the cost-performance competition it was proved that the quality can't be assured by inspection. A more advantageous way is to plan the quality in the very beginning of the development process rather than inspect during the production processes and in the worst case correct at the customer. These facts constrained the quality-conscious organizations to concentrate on the optimization of product design.

Development of such products and processes where the number of quality influencing factors are high, the use of the experimental design method is proposed. The method makes possible to identify those factors which affect significantly the quality characteristics of a product and the deviation of these characteristics from the target values. Furthermore the regression model related to the relationship between factors and response values can be determined, the optimal factors' level established. Knowing these relations the product's and process' properties can be designed in the very beginning of the development phase, their sensitivity to the disturbing effects minimized i.e. robust products and processes obtained.

The main aim of this research is to develop a completely new product from the sliced veneer residue for structural uses also, to optimize its elastic properties using the experimental design and response surface methods, to determine stochastic models of product's characteristics.

2. Aims of the research work:

- In the *first phase* of the research work a preliminary investigation was conducted to analyze the applicability of the sliced veneer residue as board- or beam-type structural product. The veneer waste is used alone or mixed with other strand-type materials. In this stage the mat formation and pressing technology is developed, the optimal proportion of the base materials and resin dosage is determined. Furthermore the effect of the production parameters on the mechanical characteristics of the components is investigated. The proposed structural application requires analyzing the orthotropic behavior of the sliced veneer's bending stiffness. The effects of bonding and pressing processes on the veneer properties are studied therewith to evaluate the occurred changes in the elastic properties. The obtained results can contribute to increase the estimation accuracy of the simulation models used for mechanical properties of engineered wood products.

- As a *second step* the effects of the raw material's characteristics and pressing parameters on the product properties are evaluated. The high number of possible influencing factors legitimates the use of a fractional factorial design with few levels. This design makes possible to involve numerous factors with relatively moderate set-ups. The analysis of the width and orientation of the veneer strips – considered important factors – implied the use of veneer strips with regular shape (parallel sides). Response characteristics investigated were modulus of elasticity, modulus of rupture, thickness swelling and interlaminar shear strength. Determining the magnitude and significance of the factors' effect makes possible to generate regression models of the response characteristics, to assign the optimal factor levels combination necessary for the best product type.

- The *last phase* of the research work is related to the analysis of technological parameters using a three level experimental design. In this case quadratic regression models can be achieved and the investigation of the Taguchi type signal to noise ratios is possible. The dry veneer residues used for experiments did not undergo any manipulation or modifications and were used exactly in the form as they come from the production process. The new product's strength properties are compared with other engineered wood products and as a result the composites can be graded. Finally the application areas and directions of the development are determined.

3. Scientific background

According to the aims of the research work the review of scientific background refers to three areas: results obtained in the engineering wood products' modeling; applications of the experimental design method in wood industry; precedent works of the ultrasonic tests in wood industry.

3.1. *Modeling engineered wood products*

Decreasing the variability of the base material and homogenizing the end products' properties were the most important goals of the engineered wood products' manufacturing. This means that wood material must be decomposed to particles with different sizes and forms (veneer, strips and strands) and bonded together into large scale products thereafter. From this point the main problem is related to the process complexity of the production line rather than to the base materials' variability. To design the final product's properties in the early stage of the development process a tight control of the manufacturing process is necessary. This supposes the exact knowledge and understanding of the whole production process. Systematic analysis and optimization of the manufacturing parameters will lead to higher composite performance, increased production efficiency. The optimization can only be realized by determining the material and production characteristics' effects on the mechanical properties of the final product.

Several models were developed to simulate the relationship between process variables and final product's physical and mechanical properties. These models try to simulate the whole process or just a fragment of it with different estimation goodness. In the most case the complexity of the manufacturing processes necessitate the use of various simplifications and boundary conditions. Depending on the parameters number and nature of the relationships between them these models can have stochastic or combined stochastic-deterministic nature.

Among the first models we find the statistical model of Suchsland which investigated the in-plane density variation known as horizontal density distribution (HDD), and determined that strand geometry affects the relative void volume in a mat (Suchsland, 1967). Later Suchsland and Xu (Suchsland, 1989) continued the investigation to develop a model for the simulation of the HDD in flakeboards. From this research it was concluded that both internal bond and thickness swelling properties were directly affected by HDD.

Cha and Pearson (Cha, 1994) elaborated a two dimensional finite element model to estimate the elasticity of elongation of a three layered plywood, where the core layer's orientation is varied. The random deposition of strand based mats was modeled with a probabilistic model by Dai and Steiner (Steiner, 1994; Dai, 1994a, 1994b). The model uses the approach that the structural properties of a randomly formed strand network are random variables essentially characterized by Poisson and exponential distributions, and predicts the distribution of the number of strand centers per unit of area, strand area coverage, free strand length and void size.

A model for viscoelastic consolidation of wood-strand mats were developed by Láng and Wolcott (Láng, 1996a, 1996b). In this model the mat structure is considered as a finite number of imaginary columns, varying numbers of overlapping strands and size of void space. The stress approximation is based on simple beam theory and compression behavior of cellular materials. The model can predict the stress response of randomly formed mats with good accuracy. An empirical model was established by Wang and Lam (Wang, 1999) to predict the relationship between the strands' slenderness ratio, orientation and the boards' density profile. Oudjehane developed a nonlinear viscoelastic model to describe and estimate the changes occurred during the mat consolidation process (Oudjehane, 1998b).

An integrated model of the effect of processing parameters on the strength properties of oriented strand products such as oriented strand board and oriented strand lumber has been developed by Barnes (Barnes, 2000), with good predictive effectiveness. The model proposes that the composite strength properties can be calculated as a product of the input wood property and eight parameter factors. The model predicts that high-strength panel and lumber products can be manufactured using OSB strands by integrated control of the process parameters, wood strength, density and resin content, strand length and thickness and the angular deviation of the strands.

Based on the properties of the constitutive wood strands, Clouston and Lam (Clouston, 2001) formulated a nonlinear stochastic model to simulate the stress-strain behavior of strand-based wood composites.

A stochastic-deterministic model based on fundamental engineering principles was developed and validated by Zombori to establish a relationship between process parameters and the final properties of wood based composite boards (Zombori, 2001). The model simulate the mat formation, then compresses the reconstituted mat to its final thickness in a virtual press. The mat formation part of the model is based on the Monte Carlo simulation technique to reproduce the spatial structure of the mat. The main advantage of this model based on that the effect of the hot-compression parameters on the final properties of wood-based composite boards can be monitored without extensive experimentation.

A Hungarian-American joint research team investigated the possibility to create a designing and predicting model for mechanical and quality characteristics of structural wood based composites. The main goal of the research was to model the mat formation process and its properties on the basis of strand characteristics and locations. Starting from the tensor theory they developed a combined model which describes the mechanical properties taking into account the angular variation of both grains and annual rings (Kovács, 2002; Láng, 2002).

Dai et al. (Dai, 2005) elaborated a theoretical predicting model to simulate the effect of the consolidation process during composite pressing to the porosity and permeability. The model considers both the inter-strand and the intra-strand gaps' variation.

3.2. *Design of experiments in the wood industry*

Examples for quality improvement with the design of experiments method are sparse in the wood industry. The method's applicability and effectiveness in this industry branch is less known. In other areas the efficiency of the method was justified therefore in this research work it is used as a new, wood based product development technique.

The use of experimental design and response surface method was successfully used to evaluate the veneer yield and quality (Warren, 1980) and to maximize the paper birch utilization in a three-layer, two-species oriented strand board (Au, 1992).

Hsu (Hsu, 1996) used the response surface method to reveal the interactions between pressing parameters (temperature, closure rate) and moisture content of the mat surface. Wang (Wang, 1999) used a central composite design to analyze the effects of strand slenderness ratio, orientation and density on the modulus of elasticity, modulus of rupture, perpendicular tension strength and thickness swelling of OSB boards.

Wood floor and wood-wool from brown salwood (*Acacia mangium*), red mahogany (*Eucalyptus Pellita*) and black poplar (*Populus x euramericana*) were compared by Semple et al. (Semple, 1999) for compatibility with Portland cement using a combined fractional factorial design. Németh used a central composite design to study and optimize the alkaline-anthrakinon pulping process of black locust (Németh, 2000).

The response surface methodology with the Box and Behnken design was used to define the minimum number of experimental points needed to fully represent a quadratic regression model in a study of volatile organic compounds (VOCs) in plywood press emissions (Barry, 2001). A two-factor factorial design with four levels was employed by Song and Hwang to investigate the mechanical properties of composites made from wood fiber and recycled tire rubber (Song, 2001). Andrews et al. studied the vertical density profile of oriented strandboard using a split-plot design (Andrews, 2001).

The glue penetration problem during the veneering process was investigated by Nagy (Nagy, 2001). He used an L27 type Taguchi design to reveal the significant factors' effect. Martínez and Calil discuss in a paper (Martínez, 2003) a statistical experimental design and an orthogonal polynomial model to estimate the fatigue strength of wooden finger joint subject to stress. The results of the test on specimens demonstrate that the orthogonal polynomial model based on a central orthogonal composite design is a good estimator of the number of cycles as a function of the stress and frequency for both real and undetermined extrapolated values.

The enumerated applications of the experimental design method in the wood industry conduct to the evidence that this technique can be used successfully for new wood product development, optimization of manufacturing processes, description of the relationships between influencing factors and response variables.

3.3. *Ultrasonic tests for wood characteristics' evaluation*

Nowadays the ultrasonic tests are among the nondestructive methods which gained ground in the wood industry too. These methods make possible the optimization of the base material's utilization, the quality control of the manufacturing processes. Their advantages consist of their integrability in the production process and in the relative low installation costs. For the wood and wood-based product's ultrasonic tests two methods are generally used: the reflection and the stress wave method (Divós, 1999).

The last one's working principle is based on the fact that solid materials are good conductors of sound waves. One way to generate these waves is realized by ultrasonic transducers which transform the electric energy into mechanical energy. The elastic wave's propagation speed correlates with many of the wood's properties (stiffness, strength, anisotropy). This correlation can be used for wood defects' detection (Divós, 2000), for the classification of base materials and final products, for acoustic monitoring of cold-setting adhesive curing in wood laminates (Biernacki, 1996).

The relationship of vibration properties to elastic characteristics was recognized as early as 1747 by Riccati (in: Bejó, 2000). Researchers started to apply this relationship and develop the ultrasonic techniques for wood in the early sixties.

The effect of the wood characteristics (e.g. grain direction and grain slope), environmental variables (moisture content, temperature) on the ultrasonic velocity propagation was studied by many researchers (Suzuki and Sasaki 1990, Mishiro 1996, Bucur 1988). The correlation of the grain slope with the propagation speed was strong in all these cases.

Ultrasonic test methods were used to determine the bonding quality of wood based composites (Ross, 1988; Beall, 1991; Biernacki, 1996), to estimate the spring-back magnitude and the internal bond strength of particleboards (Sun, 1998), to reveal both surface and internal checks developed during lumber drying (Fuller, 1994), to determine the lathe checks of technical veneers (Wang, 2001a), to detect the delaminating area of plywood (Iancu, 2000).

Wang and Chen investigated the efficiency of flake's alignment and orthotropic properties of oriented strand board by using ultrasonic wave method. As a result the correlation among ultrasonic velocity, dynamic modulus of elasticity, modulus of elasticity in bending and modulus of rupture was determined. These interrelationships could be described by linear regression formulas.

The linear relationship between the dynamic and static modulus of elasticity was demonstrated in many studies for example in Passialis and Adamopoulos, Ilic, Divós, etc. (Passialis, 2002; Ilic, 2001, Divós, 1997).

According to the scientific background studies it can be concluded that the usability of ultrasonic methods are high in the wood industry and can be utilized from the classification and characterization of wood and wood based products to the wood defects and bonding quality detections.

4. Materials and methods

First trials of the research work were executed at the Division of Forestry, West Virginia University. A mix of three frequently used species for decorative veneer production in the Appalachian region has been involved as raw material. These included about 60% black cherry (*Prunus serotina*), 35% red oak (*Quercus rubra*) and 5% maple (*Acer spp*.) for all panel types.

The dry veneer residues did not undergo any manipulation or modifications and were used exactly in the form as they come from an Appalachian decorative veneer manufacturing plant. An industrial phenol-resorcinol formaldehyde type adhesive (50% solid content) provided adhesion between the constituents. The resin application took place in a laboratory drum blender.

Hand mat forming in an 80 cm x 72 cm forming box ensured high degree of control in parallel alignment of long strands. However, the inherent edge effect could not be eliminated. Stop bars controlled the final thickness (18.5 mm) of the composite panels during the consolidation. A 200 ton capacity, one daylight, hydraulic hot-press applied the consolidation pressures to achieve the target densities. Press platen temperature was 135 ± 2°C for all panels with approximately 35 minutes closed time and a 2 to 5 minutes venting time. The consolidation pressure varied according to the target densities. From each panel, 8 specimens (750 mm long, 76.2 mm wide) were cut and conditioned at 21 ±3 °C and 65 ± 1% RH prior to testing for bending strength and apparent modulus of elasticity. All tests followed the specifications of relevant ASTM standards.

The orthotropy of the dynamic and static MOE was investigated using ultrasonic technique and paper-bending equipment respectively. The experiment included two hardwood species grown in Hungary, namely beech (*Fagus silvatica* L.) and maple (*Acer pseudoplatanus* L.). Two-dimensional Hankinson-formula with variable exponent as well as an equation based on four-dimensional tensor as functions of the grain angle was fitted to the observed values.

The effects of composite manufacturing parameters were simulated by curing the phenol-formaldehyde type resin (solid content 40%) spread on individual veneer layers using hot press conditions. Resin coverage was realized using a roller coater machine with an application rate of 75 g/m^2. For a better simulation the covered veneers were placed in a veneer bundle. The pressing parameters were as follows: press platen temperature 145°C; pressure 1,5 MPa; press time 10 minutes. The ultrasound propagation speed was measured in every 15 degrees before and after the modification. To compare the dynamic and static modulus of elasticity both unmodified and modified veneers were subjected to a two point bending test.

The effects of two material characteristics, three mat forming and two pressing parameters on the composites mechanical properties were investigated using a fractional factorial design with 16 set-ups. The selected factors and their setting levels are presented in ***Table 1***.

Table 1.

	Factors	**Level 1**	**Level 2**
1	x_1 – Species	beech	maple
2	x_2 – Strand width	15 mm	35 mm
3	x_3 – Overlapping	0%	50%
4	x_4 – Thickness	35 layer	75 layer
5	x_5 – Strand orientation	15°	30°
6	x_6 – Pressure	2,16 MPa	3,14 MPa
7	x_7 – Pressing temperature	130°C	160°C

The method of spreading the phenol-formaldehyde type resin was similar to the previous technology. Veneers moisture content measured before resin covering was 2,2-4,2%. From the narrow veneer strips with uniform width an oriented and cross-layered panel structure was produced using a laboratory hot press. Pressing time determination was realized using a Molybdenum-Copper thermocouple.

The following mechanical and physical properties were determined:

- flatwise modulus of elasticity
- edgewise modulus of elasticity
- flatwise modulus of rupture
- edgewise modulus of rupture
- thickness swelling
- interlaminar shear strength

In the last research phase the effect of three technological parameters on the flexural properties of the newly developed composites were studied using an L9 type Taguchi design. Experiments were completed at the Division of Forestry, West Virginia University, the raw materials; their proportions and the manufacturing technology coincide with the first trials'. To analyze the quadratic effect of the selected factors three setting levels were determined for each of them. In order to evaluate the flexural properties as a function of technological conditions, the adhesive content, final density and end-clippings content were selected as design variables at three levels summarized in ***Table 2***.

Table 2.

Factors	Levels		
	1	**2**	**3**
A –Resin content – R_t, %	5	8	11
B – Target density – ρ_l, kg/m^3	650	700	750
C – Ratio of end clippings – V_t, %	0	25	50

Choosing three setting levels of the factors was justified by the curvilinear relationship of the resin content and strand length against the mechanical properties in the case of oriented strand products. The L_9 design allows the evaluation of 4 factors. Therefore, beside the three controllable processing parameters investigated, the unknown effects can be considered pooled together along with the experimental error in column 4 of the design matrix. These unknown effects include the effect of the so-called inner noise factors, such as tolerances of the processing parameters, natural irregularities in material properties, the effect of outer (environmental) noise factors as well as possible interactions of any factors.

The experimental design required the manufacture of nine composite panels. From each panel, 8 specimens (750 mm long, 76.2 mm wide) were cut and conditioned at 21 ±3 °C and 65 ± 1% RH prior to testing for bending strength and apparent modulus of elasticity. All tests followed the specifications of relevant ASTM standards.

5. Results and discussion

Surveys and estimations related to the European wood resource evolution shows that the quantity and quality of the available industrial roundwood will significantly change in the future. According to the prognoses sufficient base materials will be produced by European forests but the quality, dimension and species composition of the wood resources will suffer considerable modifications. This phenomenon involves the revision of the conversion processes too. For that reason the research and development activities must concentrate on the optimal and efficient utilization of the altered wood resources; to develop new, flexible and environmental-friendly technologies; to reuse and recycle the residues and wastes occurred during processing. Another important possibility of the resource conservation lies in the manufacturing of robust products which are resistant against environmental variations. As a result new wood based products appeared fulfilling the above mentioned requirements. Among the new developments we find the engineered wood products (LVL, PSL, LSL, and OSB), the wood-plastic composites, and modified wood which are capable to comprise the previous viewpoints. An important recycling waste may be the clipping residue of the sliced veneer manufacturing because of its very favorable shape and structural properties.

The whole research project investigates the recycling possibility of clipping wastes in a form of board- and lumber-type products applicable for structural use. The study analyzes the effects of important factors on the composites' physical and mechanical properties. Taking into account the significant decorative veneer quantities produced in Europe the research is justified from the economical viewpoint also.

In the first phase of the research and development process a mix of three frequently used hardwood species for decorative veneer production in the Appalachian region was utilized black cherry, red oak and maple respectively. From this mixture different composites were produced in various structure and stratification. The elastic properties of composites proved that the clipping residues can be converted into new products applicable for structural use also. The residue is usable both in itself and with other strand type materials. The properties of the new product can be designed and controlled by changing the mixture ratio and strand orientation.

Beside the new product development the anisotropy of static and dynamic modulus of elasticity was investigated using two hardwood species grown in Hungary beech and maple respectively. The relationship between the ultrasound propagation speed and dynamic modulus of elasticity was determined in function of the grain angle. Both the generalized Hankinson formula and an equation based on four-dimensional tensor show a good fitting to the observed values. Analyzing the influence of the species on the propagation speed comes out that this effect is significant in the 0-15° range only and from 15° the effect of the resin is predominant. It was established that gluing and subsequent hot-press curing resulted in a close to linear increase of the apparent MOE of the individual veneer stripes as a function of the grain angle. As a result of the investigation, we obtained a useful database for producing the random material property input for a probabilistic simulation model in order to predict flexural properties of composite material made of sliced veneer waste in from of stripes. The static modulus of elasticity was measured using a paper-bending equipment and shows significantly lower values than solid wood’s one. The measurements accuracy can be increased by taking into account the slicing checks’ depth.

Characterization of multilayered, strand-type composites represents real challenges because of the extreme variations in physical and mechanical properties of the constituents. Further inconsistencies may originate from uneven resin distribution and from the more or less stochastic nature of different forming processes. Experimental design techniques can be very useful in establishing statistical control of a process influenced by numerous factors. The method makes possible to evaluate the effect of several factors, to model mathematically the relationship between the selected parameters and response characteristics, to determine the optimal setting levels of the factors. A product or process improved in this way is called robust and the methodology is known as robust parameter design (RPD). The technique was introduced by Taguchi (Taguchi, 1987) to improve the quality of a product through minimizing the effect of the environmental or noise factors by changing the setting levels of controllable variables. The method relies on the design of experiment (DOE) theory using orthogonal arrays to study the parameter space. Taguchi proposed the use of separate designs for the two types of variables: the controllable factors are placed in a so-called inner array and the uncontrollable ones comprise an outer array. The set of experiments are completed according to the Cartesian product of these designs. To reduce the number of the experimental runs, one can use a combined array (Nair et al. 1992) which incorporates both controllable and noise factors. Taguchi defines a performance measure called signal-to-noise ratio (SN) derived from the quadratic loss function, which calls for simultaneous optimization of the mean and standard deviation. For different optimization problems, a number of distinct SN ratios exist depending on whether the quality characteristic should have a definite target level or, on the contrary, approaching an extreme either low or high value is more satisfactory.

Application of the method allows an off-line quality control, reduction of losses due to the products’ quality characteristics variation. Using the proper loss function the customers’ global financial losses and cost savings by variation decrease can be determined. However some of the experimental designs proposed by Taguchi have a strong confounding system which leads to inconsistent results unless we know the interactions' magnitude of the effects. The efficiency of the method can be increased by using additional experimental designs.

As a second step of the research effectuated at the University of West Hungary, Faculty of Wood Science the effects of material characteristics, mat formation and hot pressing process on the veneer composites' physical and mechanical properties were investigated. Seven factors were selected totally and four response characteristics were analyzed (modulus of elasticity, modulus of rupture, thickness swelling, interlaminar shear strength). A 2^{7-3}_{IV} type fractional factorial design was employed to screen out the factors' effect and to determine the regression models of the response characteristics. The selected experimental design enabled to determine the seven factors' main effect but didn't permit to evaluate independently the second order interactions proved to be significant.

By identifying the most important factors, which influence the elastic and strength properties of the composites one can conclude that the thickness, the orientation and the consolidation pressure are the most influential variables. Both the average values and factors' effect magnitude vary in function of the load direction. In the edgewise direction these values are significantly higher. The three replications of the experimental set ups made possible to evaluate the reproduction error; to verify the adequacy of regression models. Neglecting the existing interactions decreased the accuracy of estimation functions. The standard deviation of the replications is much higher than that the deviation between groups. The dispersion can only be decreased by decreasing the average values.

Thickness swelling values of the newly developed composite are favorable and reducible by choosing an optimal factor level combination. Thickness swelling is influenced just by species but the regression model contains the veneer strip width and pressure too with *p* values less than 0,25. The reduced model is adequate and shows a good fitness on the measured points.

Comparing the interlaminar shear strength of the veneer composites with similar engineered wood products ($\tau_{//LSL}$= 2,8; $\tau_{//PSL}$= 2,2; $\tau_{//OSB}$= 1,38-2,1 N/mm^2) the structural application of the products is justified. The coefficient of variation of the composites manufactured from beech shows a higher value then of maple boards. The stability of the latter's are significantly higher both from the average and variation viewpoints. Analysis of variance of the factors' effect reveals the insignificant influence of strand width and overlapping the regression model of the remaining effects fits quite well to the measured points. Improving the composites bonding quality will possibly lead to higher shear strength values.

The experimental results obtained in this chapter confirmed again that the decorative veneer's clipping residues are suitable for board- and lumber-type engineering wood product manufacturing with favorable flexural properties. The developed models that predict the effects of critical variables on the mechanical properties of the composites allow robust product designs and optimisations at the manufacturing facilities. Further refinements of the manufacturing technology can lead to improved physical and mechanical properties of the composites.

In the last phase of the development process the effect of resin content panel density and end clippings content were investigated using an $\mathbf{L_9}$ type Taguchi design. The average MOE and MOR values of the new composites are very much comparable to strength and stiffness of similar products currently on the market. Some increase in strength may be attributed to the densification beyond target values. However, after adjustments by regression technique, the strength and stiffness values still remained at very satisfactory levels.

Analysis of Variance (ANOVA) at $\alpha = 0.05$ level identified the statistically meaningful effects of some of the factors on the flexural properties. Having been performed a three level factorial experiment; it was possible to analyze not just the linear ($_L$) but the quadratic ($_Q$) effects of the factors. The results of ANOVA indicated that two main linear effects, final panel density and end clippings content had significant influence on the flexural properties. Analyzing individually the effects of factors, it can be concluded that adhesive content in the selected range plays an insignificant role while as demonstrated by other researchers, density has a positive linear effect on the examined mechanical properties. In contrast, end-clipping contents have a near linear negative effect on the expected stiffness of the products.

Both the experimental mean values and the SN ratios indicate the same trends in factorial effects i.e., with an appropriate choice of the scale in the case of SN_L the curves essentially coincide. This is because none of the factors has any major effect on process variability, hence both the experimental means and SN_L ratios measure location effects only, and the ranges of projected standard errors are akin. These facts pointed out that no additional information could be gained. Thus, the use of the signal to noise ratios had been eliminated from further analyses.

In the case of modulus of rupture (MOR) don’t appear statistically significant quadratic effects. However, the comparatively wide ranges of experimental errors impaired the significance of these factorial effects. Due to the edge effect phenomena, the designed target densities were exceeded in all cases by about 5 to 55 kg/m^3. First order polynomial regression analyses helped to adjust both MOR and MOE experimental values. As a result, the standard error of experiments decreased substantially. Therefore, these adjusted values were the basis of further model developments.

The modulus of elasticity and modulus of rupture quadratic response model equations in terms of factors and real number levels after density adjustment were determined.

The coefficients of determination values $R^2 = 0.88$ and $R^2 = 0.925$ for MOE and MOR, respectively confirmed that the models adequately estimate the true response functions. The second order equations may be converted into multiple series of response surface plots, where one of the independent variables is fixed at a certain level, while the changes of the attribute in question is plotted as a function of the other factors. It is clear from the plots, that the optimal process conditions, resulting in the best performance of the products, are the extremes of the variation intervals of the two factors (i.e., maximum density and minimum end-clipping content). However, the content of end-clippings influences the performance negatively at a far less rate than does the density in the positive direction. The contour plots in the ***x-y*** planes characterize the constant responses indicating that there are many combinations that may provide desirable performance of the products. The method of steepest ascent can determine the direction of maximum increase in response. However, in real-life optimization, several other related factors still need to be considered.

As previously has been demonstrated, decorative, hardwood veneer residues can be successfully converted into structural composites. Results of this segment of the research demonstrated that the flexural properties can be further manipulated to desired values by changing the levels of two key factors: density and short-furnish content. Analyses revealed that resin content had insignificant influence on strength and stiffness of the products within the examined range of levels. Contrary to the a priori hypotheses the quadratic effects of the resin content and end-clipping content are not significant in the selected variation interval.

Although the use of Taguchi's signal-to-noise ratios did not confer additional information for this particular case, the described statistical method to control manufacturing processes and the response surface models provided useful information for strand type composite development. The advantages of these methods are the flexibility, expandability and their strong statistical background.

6. Theses of the Doctoral (Ph.D.) Dissertation

I. The recycling possibility of the hardwood (beech, maple, black cherry, red oak) decorative veneers' clipping waste as board-type composites was investigated by the author for the first time. The laboratory experiments proved that high-strength products applicable for structural uses can be produced from the clipping residues using the base material either in itself or mixed with other strand–type materials.

II. The plane anisotropy of modulus of elasticity in the case of sliced veneers produced from beech and maple species was investigated using ultrasonic and static test methods. To simulate the manufacturing effect veneers were covered with phenol-formaldehyde resin and the curing process took place in a laboratory hot press.
Statements:

- The plane anisotropy of modulus of elasticity can be estimated with good agreement by both two-dimensional Hankinson formula and an equation based on four-dimensional tensor theory. The modified Hankinson formula's optimal exponents are as follow:
    - For the anisotropy of ultrasound velocity: n = 1,88 in the case of untreated veneers; n = 1,78 in the case of veneers covered with phenol-formaldehyde resin.
    - For the dynamic modulus of elasticity: n = 2,25 in the case of untreated veneers; n = 1,99 in the case of veneers covered with phenol-formaldehyde resin.
- Difference between untreated and treated veneers' dynamic modulus of elasticity is caused by the different densities of the species and the density increasing effect of the resin in a range of 0-15° of the grain angle. At higher grain angles the compaction effect and the slicing check filling effect of the resin are added.
- Covering the veneer's surface with phenol-formaldehyde resin will significantly modify the sliced veneers' elastic properties therefore this effect must be taken into account when final product model is prepared. In the interval of 0-10° of grain angle the dynamic modulus of elasticity corrected by the density increase doesn't change significantly, between 10 and 75° the modulus of elasticity increase of the treated veneers is nearly linear and can be estimated with the equation:

$$MOE_{dm} = 1 + 0{,}0101 \cdot MOE_{dsz}$$

  In the range of 75 to 90° of grain angle the variation is statistically insignificant.

III. The author used for the first time in Hungary large fractional factorial as well as Taguchi designs to develop a new veneer-based composite. Utilization of these designs made possible to reveal the important factors which significantly influence the elastic strength and stiffness, interlaminar shear strength and thickness swelling of the new composites. These factors are as follows: orthotropy of the raw material, density, species, pressure and end clippings content respectively. In the selected variation interval of the factors the veneer strip width and overlapping effects were not statistically significant.

IV. Investigating the effect of species, mat formation and pressing parameters on the composites' physical and mechanical properties using 2^{7-3}_{IV}, 2^{6-3}_{III} type fractional factorial designs lead to the following statements:

- Based on the utilized press cycle the modulus of elasticity was mostly influenced by composite's final thickness, veneer strips orientation, pressure and species. The factors' effect changes in function of the load direction (flatwise or edgewise). Beside the main effects there are some significant second order interactions but the confounding system doesn't allow estimating them independently. The regression models of the modulus of elasticity in function of the load direction are:

$$\hat{y}_{MOE_{flatw}} = 9613 - 404x_1 - 117x_2 - 239x_3 - 1367x_4 - 1833x_5 + 684x_6 + 446x_7 + \\ + 464x_1x_2 + 316x_1x_3 + 640x_1x_4 + 339x_1x_5 - 529x_1x_6$$

$$\hat{y}_{MOE_{edgew}} = 10236 - 894x_1 + 53x_2 - 1144x_4 - 1646x_5 + 681x_6 + 18x_7 + 342x_1x_2 + \\ + 409x_1x_4 - 573x_1x_6 + 268x_1x_7$$

- The thickness, strip orientation, pressure and pressing temperature have significant influence on the composites' modulus of rupture. In the case of interactions the above mentioned statement is valid. The regression models are as follows:

$$\hat{y}_{MOR_{lap}} = 72 + 0{,}22x_1 + 2{,}07x_2 - 30{,}16x_4 - 9{,}62x_5 + 5{,}65x_6 + 4{,}74x_7 + 4{,}08x_1x_2 + \\ + 7{,}54x_1x_4 - 3{,}18x_1x_7$$

$$\hat{y}_{MOR_{el}} = 90{,}3 - 4{,}84x_1 + 1{,}6x_2 - 4{,}48x_3 - 13{,}5x_4 - 10{,}82x_5 + 5{,}85x_6 + 3{,}73x_7 + 1{,}58x_1x_2 \\ + 1{,}69x_1x_3 + 3{,}37x_1x_4 + 2{,}43x_1x_5 - 3{,}62x_1x_6$$

- The composites' thickness swelling is influenced mainly by the species, the next polynomial model is valid:

$$\hat{y}_{G_t} = 9{,}08 - 2{,}3x_1 + 0{,}4x_2 + 0{,}44x_6$$

- Analysis of results related to the interlaminar shear strength revealed the significant influence of the species and pressure. The regression model has the form:

  $$\hat{y}_{f_r} = 4{,}341 + 1{,}121 x_1 - 0{,}24 x_5 + 0{,}631 x_6 + 0{,}244 x_7$$

V. The effect of three technological parameters (resin content, final panel density and end clippings content) on the panel's elastic properties was studied using an L_9 –type Taguchi design. According to the analysis the following statements are valid:

- The resin content in the range of 5-11% of the variation interval has no significant effect on the flexural properties
- The factors' quadratic effects are non significant
- The modulus of elasticity and modulus of rupture response model equations in terms of characteristic strength values after pooling the non-significant effects in the residuals, turned out to be as follows:

  $$\hat{y}_{MOE} = -5932{,}25 + 27{,}21 \cdot \rho_l - 38{,}03 \cdot V_t$$

  $$\hat{y}_{MOR} = -153{,}14 + 43{,}257 \cdot R_t - 2{,}53 \cdot R_t^{\,2} + 0{,}113 \cdot \rho_l - 0{,}712 \cdot V_t$$

- The optimal setting levels of the factors using a desirability function are as follows: resin content – 10%; final panel density – 750 kg/m3; end clippings content – 0%.

7. Publications related to the dissertation

A. Publications in Hungarian:

1. DÉNES L., 2003: Developing products with designed properties using the experimental design method. Applied mathematics and mechanics conference– Hungarian Science Day Proceedings, Sopron, 2003.
2. DÉNES L., KOVÁCS ZS., 2003: Application of the experimental design method for new product development. Wood Industry 51(1): 22-27. ISSN: 0014-6897
3. DÉNES L., KOVÁCS ZS., BÁLINT ZS., LÁNG E., 2002: Orthotropic elasticity of sliced veneers – Part II. Wood Industry 50(3): 21-24.
4. KOVÁCS ZS., DÉNES L., BÁLINT ZS., LÁNG E., 2002: Orthotropic elasticity of sliced veneers – Part I. Wood Industry 50(2): 3-7.
5. DÉNES L., 2001: Quality improvement using the Taguchi method, pp. 77-100 In: Proceedings of the Union of Hungarian Ph.D.-students And Young Researchers from Romania: Volume II., Kriterion Publisher, Bucharest. ISBN 973 26 0628 2

B. Publications in English:

6. ZSOLT KOVÁCS, LEVENTE DÉNES, 2005: Innovative wood composites from veneer residues, Proceedings of the 5th International Conference of Innovation-Technics-Education IN-TECH-ED'05, 8-9 september Budapest Tech
7. LEVENTE DÉNES, ELEMÉR LÁNG, ZSOLT KOVÁCS, 2004: Product development from veneer-mill residues: An application of the Taguchi's method, Wood and Fiber Science (accepted for publishing, expected to appear in January, 2006)
8. LEVENTE DÉNES, ELEMÉR LÁNG, ZSOLT KOVÁCS, 2004: Innovative wood composites from veneer residues, Proceedings of the International Symposium on Advanced Timber and Timber-Composite Elements for Buildings, COST E29 Action, Florence
9. FERENC DIVÓS, LEVENTE DÉNES, GUILLERMO INIGUEZ, 2004: Effect of cross-sectional change of a board specimen on stress wave velocity determination, Holzforschung Vol 59(2): 230-232 pp.
10. LEVENTE DÉNES, ZSOLT KOVÁCS, 2003: Analysis of the Flexural Properties of sliced veneer Waste Composites Using Experimental Design Method, Proceedings of the 4th International Conference of PhD Studies, Miskolc.

C. Oral presentations in Hungarian:

1. DÉNES L., KOVÁCS ZS., LÁNG E., 2004: Property optimizations of the engineered wood products by the experimental design method, International Conference: Wood Scientists from the Sopron Alma Mater in the World, Sopron, szeptember 16, 2004

2. DÉNES L., 2003: New product design using the experimental design method. Applied mathematics and mechanics conference– Hungarian Science Day, Sopron, 21 November 2003.
3. DÉNES L., 2002: Engineered wood products; Veneer based composite manufacturing with designed characteristics using the experimental design method. Scientific Students Conference, Brasov, 30 Nov.-01 Dec. 2002.
4. DÉNES L., 2002: Application of the experimental design method for new product development. Hungarian Science Day, Sopron, 28 November 2002.
5. DÉNES L., 2001: Parallel strand lumber (PSL) type products. Wood Industry – 2001, Conference of the Hungarian Scientific and Technical Association from Transylvania, Odorheiu Secuiesc, 16-19 May 2001.
6. DÉNES L., 2001: Veneer-based composite manufacturing with designed properties. II. Scientific Conference of the Union of Hungarian Ph.D.-students And Young Researchers from Romania, Cluj Napoca, 6-8 April 2001.
7. DÉNES L., 2000: The Taguchi-type loss function. Wood Industry – 2000, Conference of the Hungarian Scientific and Technical Association from Transylvania, Odorheiu Secuiesc, 17-21 May 2000.
8. DÉNES L., 2000: The Taguchi method for quality improvement. I. Scientific Conference of the Union of Hungarian Ph.D.-students And Young Researchers from Romania, Cluj Napoca, 11-12 March 2000.

D. Oral presentations in English:

9. LEVENTE DÉNES, 2005: Orthotropic behavior of sliced veneer changed by technological parameters, International Conference of Hardwood Research and Utilization in Europe, New Challenges, 6 September 2005 University of West Hungary, Sopron
10. LEVENTE DÉNES, ELEMÉR LÁNG, ZSOLT KOVÁCS, 2004: Innovative wood composites from veneer residues, International Symposium on Advanced Timber and Timber-Composite Elements for Buildings, COST E29 Action, Florence
11. DÉNES L., 2004: New hardwood composite development on a sliced veneer residue basis. PhD seminar „New processes in the Forest Products Industry”, Georg August University, Faculty of Forestry and Forest Ecology, January 13, 2004, Goettingen.
12. DÉNES L., 2003: New hardwood composite development. Issues of Hardwood Research and Utilization in Europe, International Conference September 25-26, 2003, University of West Hungary, Sopron.
13. DÉNES L., 2003: Analysis of the Flexural Properties of Sliced Veneer Waste Composites using the Experimental Design Method, 4th International Conference of PhD Studies, august 11-17, 2003, Miskolc.