

# Development of a One-Step Process for Production of Foam Core Particleboards using Rigid Polyurethane Foam

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A simulated one-step process has been developed for the production of foam core particleboards using rigid polyurethane as the core layer. The results showed that the different techniques used for surface layer separation (unresinated particles and sprayed water) and foam injections (open system and closed system) had no influences on panels' characteristics. Mechanical properties (e.g., bending strength and internal bond strength) were mostly influenced by the surface layer thickness, while the water absorption and edge screw withdrawal were influenced by the foam cell structure. The use of sprayed water for surface layer separation doubled the formaldehyde emission (FE) of the panels. The addition of urea (based on 10% of the dry resin) to the sprayed water had a positive effect of reducing the final FE. Furthermore, increasing the surface layer thickness had a positive, linear relationship with FE.

*Keyword: Foam core particleboards; Lightweight; Sandwich; Polyurethane; Rigid foam*

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## INTRODUCTION

Sandwich structures show promising lightweight features for use in the marine and aviation industries and have been used for decades (Gruenewald *et al.* 2015). Furthermore, lightweight boards have a significant effect on lowering the overall greenhouse gas emissions (Feifel *et al.* 2013). The use of the sandwich strategy in furniture industries is not well developed because of the time-consuming manufacturing methods, which still prevent extensive application. The second critical step for the manufacturing of sandwich structures is the joining of prefabricated skins and the lightweight core layer. The main manufacturing methods (which are already in the market) are either a batch process, where the prefabricated layers are glued and assembled together, or a process where a foaming liquid, to form the core material, is injected between two prefabricated face layers (Allen 1969; Li *et al.* 2014). The disadvantages of these processes are the lack of simultaneous production of all layers together and some restrictions regarding the production techniques.

Among all processes, the one-step process (*in-situ* foaming) shows great potential for simplifying the manufacturing process as well as joining the sandwich skins and core (Zenkert 1997). Luedtke (2011) and Shalbafan *et al.* (2012) have shown that the one-step process of forming sandwich structures has great potential for the production of lightweight foam core particleboards. The characteristics of the core layer materials, e.g., their thermoset or thermoplastic natures, pose challenges in the one-step manufacturing process. In the case of thermoplastic materials, an internal cooling for panel stabilization is essential

at the final production stage in the press. Shalbfan *et al.* (2012) have mentioned that the core layer materials should have an expandable solid-state granular shape to be used for the one-step manufacturing process of foam core particleboards. On the other hand, the use of thermosetting foam materials as core layer materials does not require internal cooling, but such materials (expandable thermosetting solid state granulates) that meet the requirements for a one-step manufacturing process are not yet available on the market.

Polyurethane (PU) is a polymer composed of organic units joined by urethane linkages. Most of the used PUs are thermoset polymers that do not need to be cooled for stabilization (Sonnenschein and Koonce 2012). The PUs are generally formed by a reaction between polyol (PO) and isocyanate (ISO) components and have a liquid phase before foaming, which presents a challenge for *in-situ* foaming. Various PU foams (soft, elastomeric, and rigid) can be produced depending on the type of polyols used for foam formulation (Ionescu 2005). Polyols with OH numbers of 300 to 500 are preferably employed for making rigid PU foams that are polyether-polyols and polyester-polyols. Rigid PU foams can be produced within a density range of around 40 to 1000 kg/m<sup>3</sup>, depending on their polyol structure. Lower density (< 60 kg/m<sup>3</sup>) is suitable for insulation applications, while higher density (> 500 kg/m<sup>3</sup>) is suitable for decorative applications (Ionescu 2005). High-density PU foams may have great performance in various applications, but the lightness effect required for a sandwich structures does not exist anymore in these foams. To reach a lightweight wood-based panels, the core layer should have a considerably lower density (< 300 kg/m<sup>3</sup>) than the conventional panels. When the core layer density is lower, the formation of lighter panels is achieved. A mixture of two different polyols (used for the insulation and decorative purposes) can induce both the lightness of the structure and great foam performances.

In this study, two different polyols, one normally used for insulation application and the other one for decorative purposes, were mixed together to reach the desired foam density and a better workability. The aim of this research is to produce foam core particleboards in a simulated one-step process (considering the challenges mentioned above) using rigid PU as the core layer. It is necessary to use surface layers separation techniques for the simulation of one-step manufacturing process. Hence, the effects of different techniques employed for surface layer separation and foam injection in the simulated one-step process were studied. The mechanical and physical properties of the panels thus produced were also analyzed.

## EXPERIMENTAL

### Materials

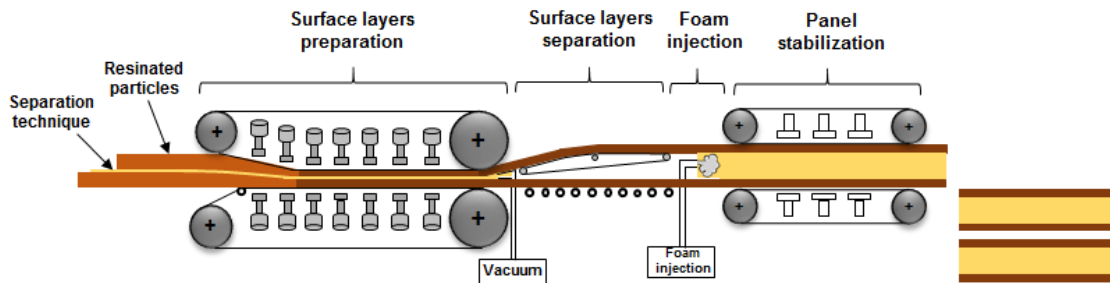
Conventional fine wood particles, primarily beech and poplar ( $\leq 2$  mm), were used for the face layers and were supplied by a local particleboard mill in Iran. The particles were mixed with urea formaldehyde (UF) (12%) resin (Amol Resin Ltd., Iran) and ammonium sulfate (1%) as a hardener. The UF resin had solid content and pH of 62% and 7.1, respectively. The target density of the surface and bottom layers was kept constant at 700 kg/m<sup>3</sup>. The surface layer thickness was varied (3, 4, and 5 mm for each of the two face layers), and accordingly, the corresponding panel density was also changed (300, 370, and 440 kg/m<sup>3</sup>).

A mixture of polyether (Kupa 501) and polyester polyols (Kupa 150) was mixed with polymeric methylene diphenyl diisocyanate (pMDI) for preparing the core layer. The

chemicals used were supplied by Jazb Setareh Co., Iran. The target density of the prepared core layer was kept constant at  $120 \text{ kg/m}^3$ .

### Test Specimen Preparation

Foam core particleboards (19 mm in thickness) were produced in a simulated one-step process consisting of four consecutive stages. The panels were produced with varying surface layer thicknesses of 3, 4, and 5 mm, and accordingly, the foam core layer varied in thickness as 13, 11, and 9 mm, respectively. The process used in this study is described in Fig. 1. In an ideal industrial one-step manufacturing process, the four consecutive stages employed are surface layer compaction, surface layer separation, foam injection, and panel stabilization. It can be stated that the most challenging stages are the surface layer separation and foam injection. Hence, various techniques were applied for layer separation and foam injection to determine their effect in such challenging stages.

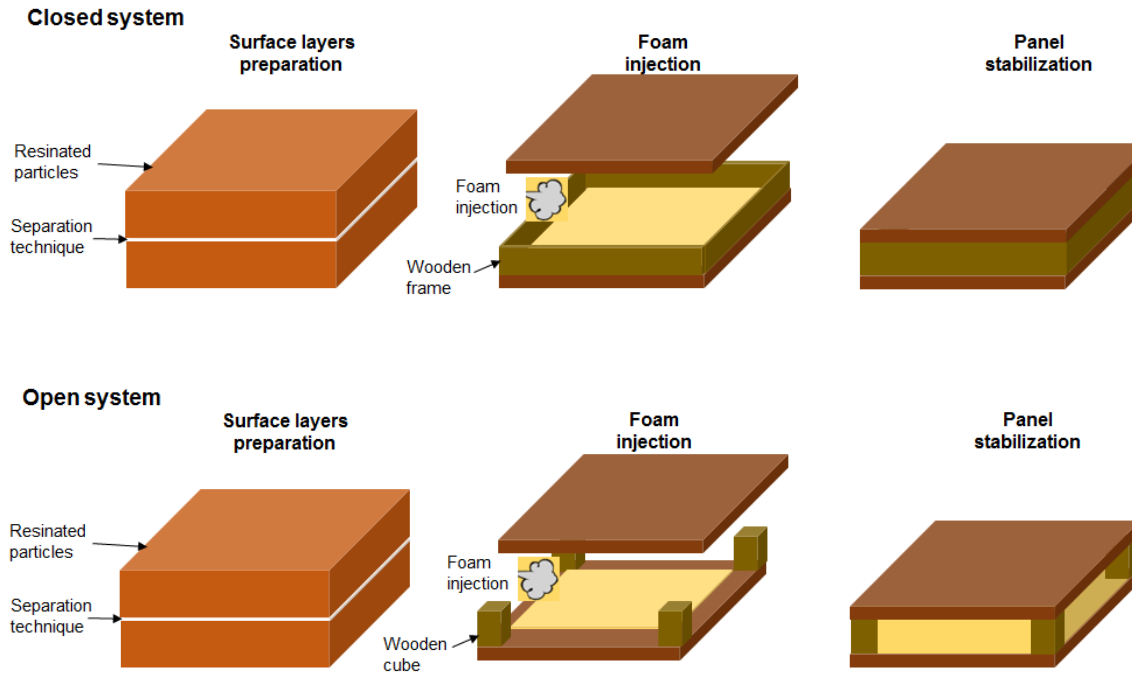


**Fig. 1.** Development of a production process for foam core particleboards in an industrial scale

The illustrated one-step manufacturing process (Fig. 1) was first simulated at the laboratory scale. To begin, the two surface layers (after particle resination and mat forming) were compacted until the UF resin was cured (at the end of the pressing section). Then, the surface layers were separated at the laboratory scale, due to the used separation techniques. Various separation techniques were carried out after the bottom layer formation and prior to the face layer formation using either un-resinated wood particles or water spray technique. Conventional fine un-resinated wood particles ( $400 \text{ g/m}^2$ ) were used as separation materials between the two layers. The amount of sprayed water on top of the bottom layer was  $60 \text{ g/m}^2$  to give rise to a steam mass (during the surface layers preparation stage) between the two layers for separation of the layers. A higher amount of sprayed water would possibly influence the foam formation and the connectivity between face-core layers. Hence, it is necessary to keep the level of sprayed water as low as possible. For the removal of the un-resinated wood particles or poorly bonded particles between the surface and the bottom layer, suction (vacuum cleaner) was used, after surface layer separation and but prior to the foam injection stage.

Two different techniques were also used for the foam injection step; either a wooden frame (closed system) or four small wooden cubes (open system) were used for this purpose. The height of the wooden frame and wooden cubes were the same as the foam core layer thickness (13, 11 or 9 mm), and they were placed on top of the bottom layer. Then, the mixture of the foam components was injected (poured) onto the bottom layer and, accordingly, the top surface layer was immediately laid on top of it. Afterwards, the whole assembly was placed on the second press (without heating zones) to keep the panel

at the desired thickness (panel stabilization). Figure 2 illustrates the simulated one-step process of foam core panel production on the laboratory scale.



**Fig. 2.** The production process for foam core particleboards at the laboratory scale: closed system composed of production with wooden frame; and open system composed of production with wooden cubes

Table 1 shows the compositions of the panel variables. To confirm the effect of face layer separation techniques on panel properties, the reference samples (using a batch process) were also produced without any separation techniques (where each surface layers were produced separately).

**Table 1.** Techniques Used for the Production of Foam Core Particleboards

Code	Surface layer separation technique*	Injection foam technique	Surface layer thickness (mm)
A	Un-resinated particles*	Closed system	3
B	Water spray**	Closed system	3
C	Water spray	Open system	3
D	Water spray	Open system	4
E	Water spray	Open system	5
F	Reference (batch process)	Closed system	3

\* Un-resinated wood particles used between the bottom and surface layers.

\*\* Sprayed water used on top of the bottom layer.

## Foam Formulations

Petroleum-based polyether polyol (Kupa 501) and polyester polyol (Kupa 150) were used after determining their hydroxyl value (450 mg KOH/g and 306 mg KOH/g, respectively) and water content (0.15% and 0.1%, respectively). A summary of the typical physical and chemical properties of both polyols (from the suppliers) is given in Table 2. The chemicals polymeric methylene diphenyl diisocyanate (pMDI), the silicon surfactant - polysiloxane ether, the catalyst - dimethylcyclohexylamine, and the blowing agent - HFC R-141b were used as received. The content of NCO groups in pMDI was 31% (according to the supplier data sheet).

**Table 2.** Physical and Chemical Properties of Polyols

Property	Test Method	Kupa 150 (Polyester polyol)	Kupa 501 (Polyether polyol)
Initiator	-	Triglyceride polyester*	Sucroseglycerol, propoxylated
Hydroxyl number, mg KOH/g	ASTM D4274	305 to 335 (306)**	430 to 445 (450)**
Viscosity, cps (25 °C)	ASTM D4878	1500-2500	3500-4500
Water (max.%)	ASTM D4672	0.15	0.1
Specific gravity (25 °C), g/ml	ASTM D4699	1.21	1.12
Color	ASTM D4890	Brown liquid	Colorless to brown

\*Aromatic polyester polyol.

\*\*Experimentally tested values.

**Table 3.** Formulations and Reactivity of Rigid Polyurethane Foams

Materials	Foam mixture
<b>Polyols</b> Kupa150 Kupa501	(pphp) 40 60
<b>Silicon Surfactant</b> Polysiloxane ether	1.5
<b>Blowing agent</b> Water HFC R-141b	0.5 10
<b>Catalyst (DMCHA)</b> Dimethylcyclohexylamine	0.6
<b>Isocyanate (pMDI, NCO%=31)</b> Percent at final foam)	135
<b>Reactivity</b> Cream time (s) Gel time (s) Rise time (s)	25 49.3 75.3

The formulation procedure for rigid polyurethane foam is summarized in Table 3. It was prepared by a two-step method. Polyols were blended with catalyst, surfactant, and blowing agent to obtain a homogenous blend according to the formulation procedure. The polyols blend was then mixed with pMDI (approximately 10 s) prior to injection. The foam reactivity data of rigid PU foam were generated from a ‘cup-test’ and are presented in Table 3 (Ionescu 2005).

### Panels Characterization

To characterize the new panels produced and to study the effect of the different techniques for layer separation and PU injection, and the effect of surface layer thickness, mechanical and physical tests were performed. Bending strength (EN 310 (1993)), internal bond strength (EN 319 (1993)), and face/edge screw withdrawal resistance (EN 13446 (2002)) were determined as the main mechanical properties. The physical behavior (EN 317 (1993)) of the panels was characterized by measuring the thickness swelling and water absorption trend after long soaking times (up to 786 h after water immersion). From each panel variation, three replicates were prepared. Three samples of each replicate ( $n = 9$ ) were randomly selected and tested. Prior to testing, all samples were conditioned in a climate chamber at 65% relative humidity and a temperature of 20 °C until a constant mass was reached. The physical tests were conducted on unsanded samples.

### Formaldehyde Emission Measurements

To further understand the properties of these novel foam core particleboards, formaldehyde emission testing was performed. The effect of surface layer thickness and sprayed water (for layer separation) on formaldehyde emission of panels was investigated using the flask method (EN717-3 (1996)). A solution of urea and water was used for spraying as the surface layer separation technique for controlling the formaldehyde emission. The amount of urea used was approximately 10% based on the solid content of resin for one face layer. More details regarding the panel variations used for formaldehyde emission was presented in Table 4.

**Table 4.** Panel Variables Used for Formaldehyde Emission Measurement

Code	Surface layer thickness (mm)	Separation technique	Foam injection
C	3	Water spray	Open system
D	4		
E	5		
F*	3	-	
K**		Urea + Water	

\*Each surface layer was produced separately (reference sample).

\*\*Solution of urea and water was used for separation of surface layers.

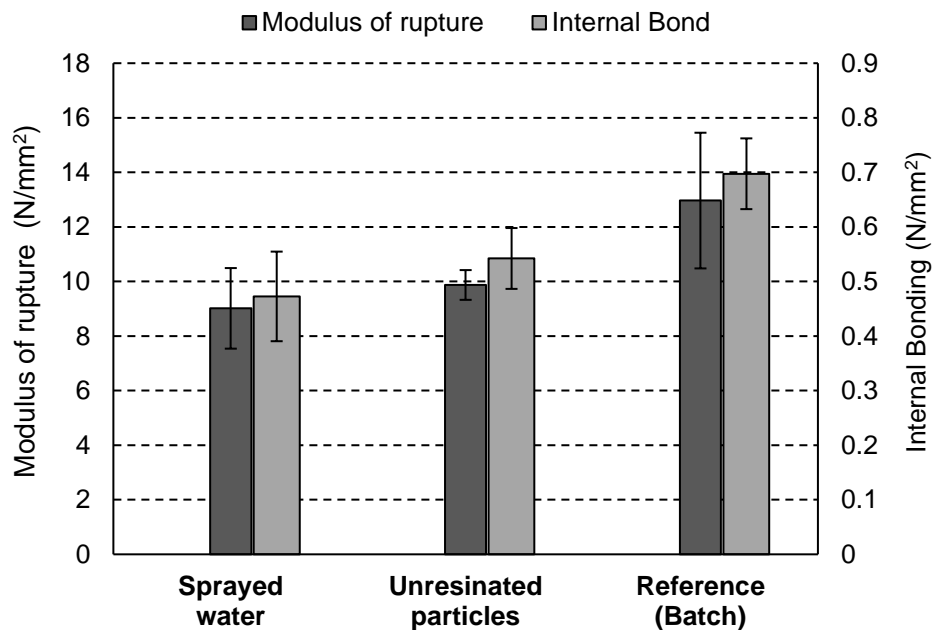
### Statistical Analysis

A two-way analysis of variance (ANOVA) of the mechanical and physical properties was performed with Statistical Package for the Social Science software (SPSS software, IBM, USA). Statistical differences between variations were evaluated by multiple comparisons based on a Duncan test because of the homogeneity of variances. A paired T-test was also used for comparing between different separation and injection technique values. The statistical significance was set at  $P < 0.05$ .

## RESULTS AND DISCUSSION

### Effect of Surface Layer Separation Techniques

One of the most important stages in developing a one-step manufacturing process of foam core panels is separation of the surface and bottom layers for foam injection. The effect of two different separation techniques (un-resinated particles and sprayed water) on bending strength (MOR) and internal bond (IB) values are presented in Fig. 3. The values of both properties (MOR and IB) for the un-resinated particles technique were slightly higher than those for the sprayed water technique, but such differences were not found to be statistically significant. The bending strength was mostly influenced by the panel density and the surface layer quality, which was nearly the same for both panel types. Internal bond values in foam core panels were influenced by the interface (face-core layer) quality (Shalbfan *et al.* 2013b). In the case of the water spray technique, a mass of water steam was shaped between the surface and bottom layers, which influences the curing of the UF-resin on the particles forming the inner sides of the face layers. Weak inner surfaces lead to a reduction in the internal bond strength values. Additionally, higher mat moisture content (in the case of sprayed water) could also lead to the reduction of adhesive crosslinking and accordingly weaken the bonding performance (Roffael 1993).



**Fig. 3.** Effect of surface layer separation techniques on bending strength and internal bond strength

A comparison of panels produced by the simulated one-step process with the ones produced in a batch process (reference samples) is presented in Fig. 3. The results showed that the reference samples had significantly higher MOR and IB values than those produced by the continuous processes. As mentioned earlier, surface layer quality because of a denser surface layer was the reason for the higher MOR values in reference samples. There was no separation technique used for producing the reference samples. Therefore, the absence of weakly bonded particles led to better adhesion with the foam components. Some weak and poorly bonded particles will always be present on the inner surfaces of the layers in

case of un-resinated wood particles and water spray separation techniques which influence the internal bond values. These weak particles did not exist in the reference samples. Although the reference samples had higher MOR and IB than those of foam core panels, they cannot be favored in furniture industry due to its batch production process (Shalbafan *et al.* 2013b).

It is worth mentioning that the minimum requirements for the IB values according to EN312/P2 were achieved for all panel variations. Although the MOR is nearly 30 percent less than EN312/P2 for the panels produced by the developed one-step process, it is still in a desirable range for special applications.

The effect of surface layer separation techniques on face screw withdrawal (FSW) and edge screw withdrawal (ESW) are presented in Fig. 4. The results showed that the separation techniques had no significant influence on FSW and ESW. The FSW was influenced by the surface layer quality, which was nearly the same for both techniques. The ESW was affected by the foam structures, which was also similar for both techniques because of the similar foam formulation.

The FSW of the reference samples was significantly higher than those panels produced by the one-step manufacturing process because it had better surface and bottom layer qualities. The ESW was not significantly changed at reference samples because the foam components were kept constant in all panel variations.

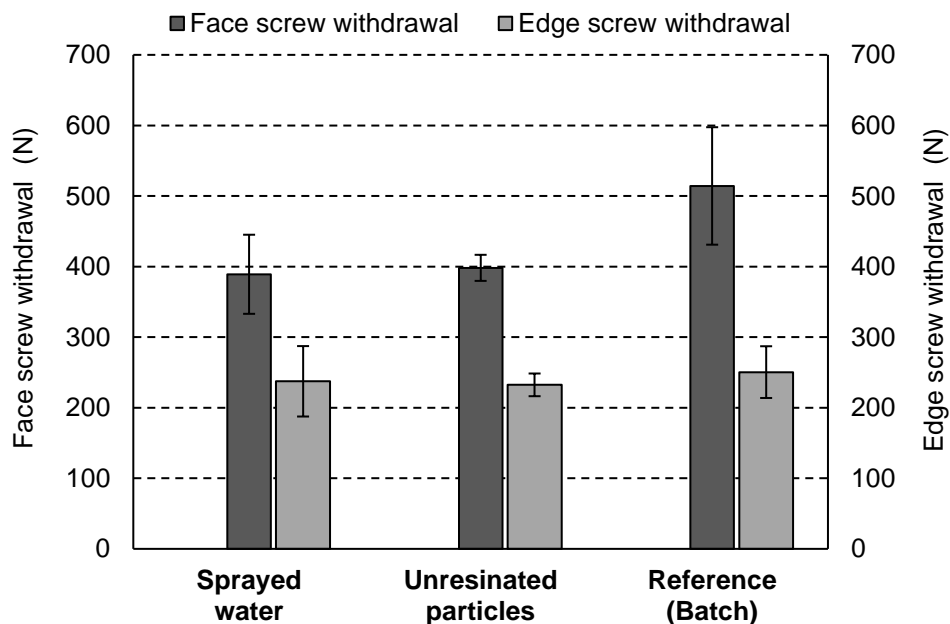


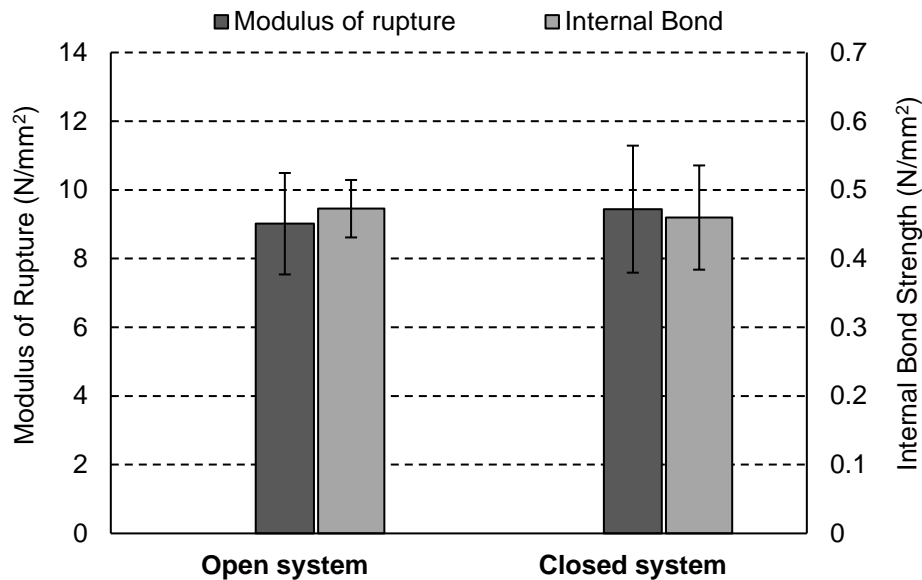
Fig. 4. Effect of surface layers separation techniques on face and edge screw withdrawal

### Effect of Foam Injection Techniques

Two different techniques (close and open systems) were used for foam injection between the separated layers. The effect of injection techniques on the bending strength and internal bond values were illustrated in Fig. 5. The results showed that different injection systems have no influence on the bending strength and internal bond strength values. It has to be mentioned that the injected (poured) foam mixture was not outpoured from the sample sides in case of open injection because of the high viscosity and very short creaming time (25 s) of the foam mixture. Additionally, visual observation showed that the

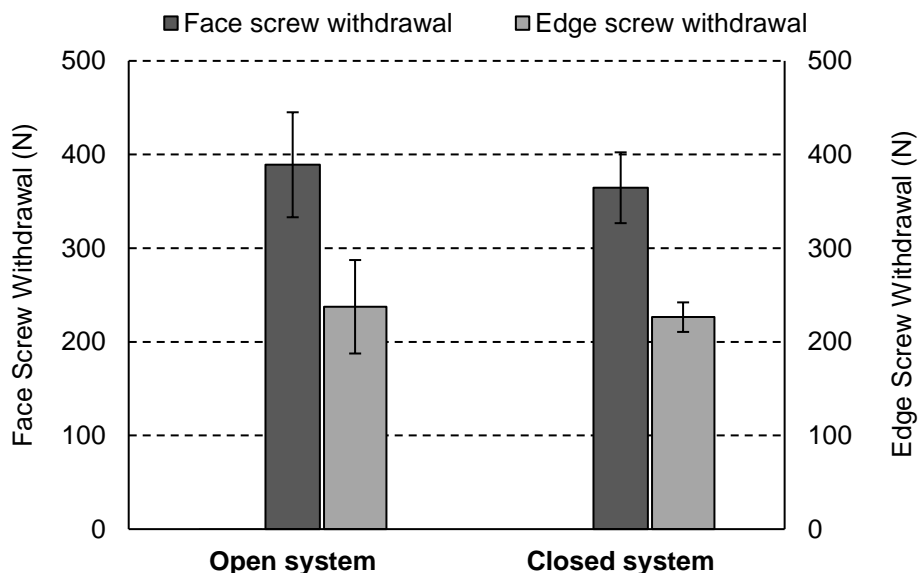


PU blend mostly moved in the height direction (rise direction), and its lateral movements were rather low. Polymeric isocyanate (pMDI) was only added to the polyols blend prior to injection. The blend was mixed for approximately 10 s and immediately poured on top of the bottom layer. Creaming of the blend happened immediately after the foam pouring (injection), and no outpouring of the foam was observed. As a final result, it can be assumed that the foam injection systems have no significant influence on the foaming process and accordingly on the panel properties.



**Fig. 5.** Effect of foam injection techniques on the bending strength and internal bond strength values

Figure 6 presents the results of face and edge screw withdrawal values for panels produced with different foam injection systems.



**Fig. 6.** Effect of foam injection techniques on face and edge screw withdrawal

The results revealed that the FSW and ESW values did not drastically vary by changing the foam injection systems. The face screw values mostly depend on the surface layers' quality which was same for both variations (Shalbafan *et al.* 2013b). The edge screw values depend on the foaming procedure and the resulting foam structure. Therefore, it can be concluded that the foam structures are nearly the same in both injection systems, as the ESW values were nearly comparable.

### Effect of Layer Thickness

The panel density and moisture content of the panels after two weeks of conditioning (at 20 °C and 65% RH) are presented in Table 5. The panel thickness remained constant (19 mm), while the surface layer thickness increased from 3 to 5 mm. Hence, the panel density was increased by increasing the surface layer thickness from 3 (302 kg/m<sup>3</sup>) to 5 mm (439 kg/m<sup>3</sup>). The moisture content was higher in panels with thicker surface layers because more hygroscopic materials exist in thicker panels.

**Table 5.** Panel Density and Moisture Content

Each surface layer thickness (mm)	Moisture content (%)*	Density (kg/m <sup>3</sup> )
3	7.59 (0.23)	302 (26)
4	8.69 (0.31)	367 (19)
5	9.11 (0.19)	439 (29)

\*Numbers in brackets are the standard deviation

The effect of surface layer thickness on the panel properties (MOR and IB) is illustrated in Fig. 7. The MOR values slightly increased, from 9.5 MPa for 3-mm panels to 10.5 MPa for 5-mm panel surface layers. The thickness, density, and structure of each layer in the foam core panels were the most important factors influencing the bending strength (Vinson 2005; Link *et al.* 2011). The density of the panels was increased by raising the surface layer thickness from 3 mm (300 kg/m<sup>3</sup>) to 5 mm (440 kg/m<sup>3</sup>). This increased panel density resulted in the increment of the bending strength. It can also be noticed that the wood became stiffer and stronger than the polymer core material. Thickening the surface layers was accompanied by reducing the foam core layer thickness from 13 to 9 mm, and accordingly higher MOR values were obtained. Chen and Yan (2012) also found that a decrease in the thickness ratio of the core of the skin layer resulted in an increase in the bending properties of the sandwich panels.

The internal bond strength values declined when the surface layer thickness was increased from 3 mm (0.46 N/mm<sup>2</sup>) to 5 mm (0.17 N/mm<sup>2</sup>). Shalbafan *et al.* (2012) have mentioned that the predominant factor that influences the internal bond strength values of foam core panels is the face-core interface quality. The samples prepared with 3-mm face thickness failed in the face layer very close to the interface, while for the ones with 5-mm face thickness, the failure occurred in the middle of the surface layers. As mentioned earlier, a mass of water steam shaped between the surface and bottom layers influences the adhesive crosslinking and accordingly weakens the bonding performance further in the thicker surface layers (Roffael 1993).

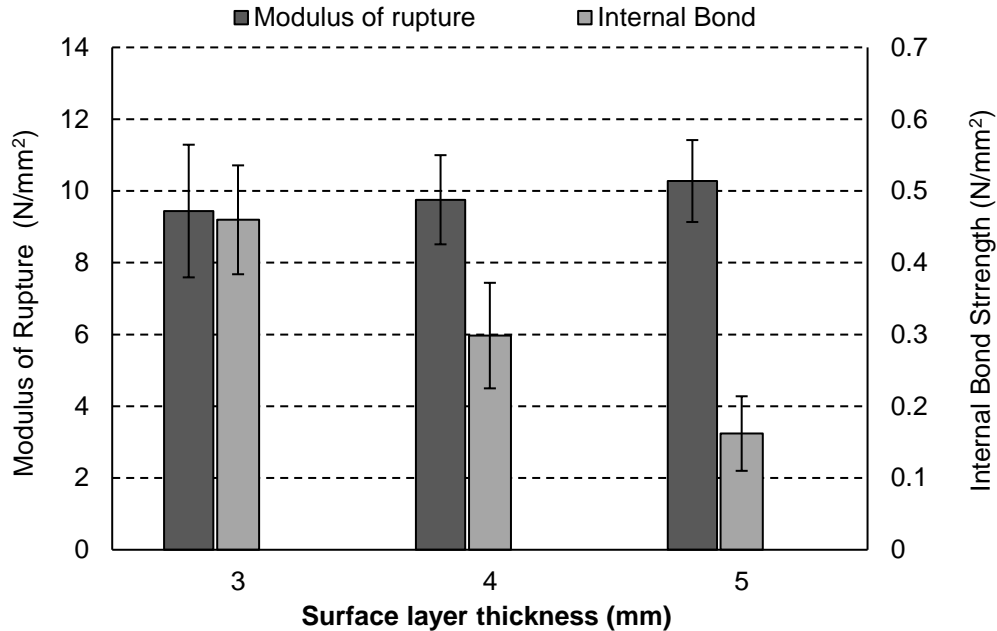


Fig. 7. Effect of surface layers' thickness on bending strength and internal bond values

The face and edge screw withdrawal values for panels with different surface layer thicknesses are pictured in Fig. 8. The results showed that the FSW linearly increased with increasing surface layer thickness. The FSW is nearly enhanced to 30% by each additional millimeter of surface layer thickness. Edge screw withdrawal values did not significantly change, and the ESW values certainly also depended on the foam formulation, but this was kept constant in all panel variations.

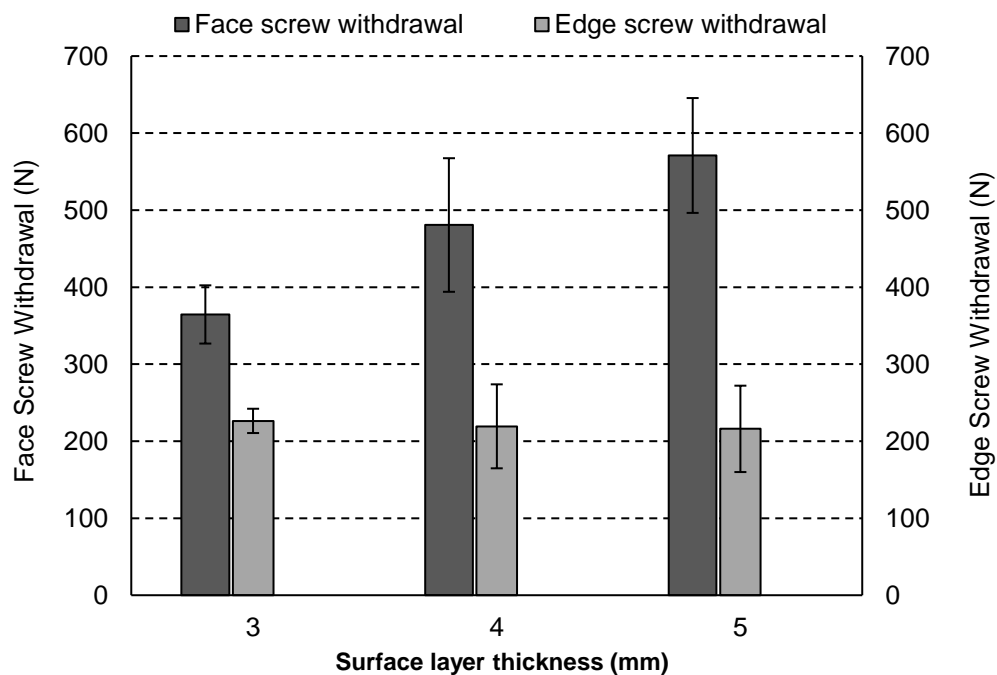
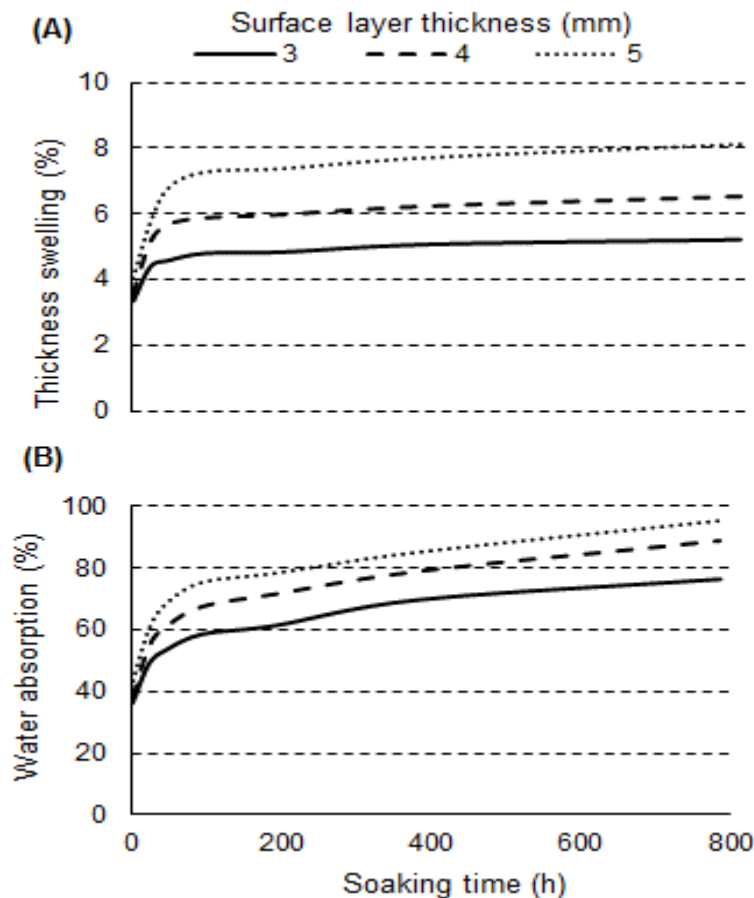


Fig. 8. Effect of surface layer thickness on face and edge screw withdrawal

The effect of surface layer thickness on the thickness swelling and water absorption for up to 786 h soaking time is presented in Fig. 9. Thickness swelling values were higher for panels with thicker surface layers. The TS values nearly reach a maximum level (5% to 7%) after approximately 48 h of soaking. Afterwards, the increase in TS was extremely reduced until reaching 786 h of soaking time, while the TS does not significantly change. The TS in foam core panels is influenced by the surface layer thickness (Luedtke 2011). It seems that the wooden particles were saturated after a short time (48 h) of soaking, and this condition does not vary with the prolongation of soaking until 786 h (Shalbafan *et al.* 2013a). It has to be also considered that the foam core layer has no influence on thickness swelling because of its hydrophobic nature.



**Fig. 9.** Effect of surface layer thickness on (A) thickness swelling and (B) water absorption

Figure 9B shows the values for water absorption of panels. The water absorption (WA) values significantly increased when the face layer thickness was increased from 3 to 5 mm. The WA values also increased steadily for all panels during soaking (from 2 to 786 h), but the speed of water uptake varied over the immersion time. An intensive absorption can be observed during the initial soaking period (48 h), and an almost linear trend can be seen for longer soaking times (from 48 to 786 h). Most of the water (> 60%) was absorbed during the initial period (48 h) of soaking. The WA values in foam core panels were affected by the surface layer (thickness and density) and foam cell structure (voids between the cells and crushed cells) (Sabbahi and Vergnaud 1993; Link *et al.* 2011). Hence, by comparing part A and B of Fig. 9, it can be stated that the surface layers are the

predominant factors influencing the WA during the initial soaking period (48 h). The water is mostly absorbed by both voids between the foam cells and crushed cells at longer soaking times (48 to 786 h). It was also worth mentioning that the WA did not stop even after 786 h of soaking time, which illustrates that the water slowly but steadily penetrates into the inner voids of the samples (Schwartz *et al.* 1989).

### Formaldehyde Emission Measurement

Formaldehyde emission (FE) from the foam core panels was determined by the flask method, as presented in Fig. 10. The results revealed that the FE linearly increased when the surface layer thickness increased from 3 to 5 mm (codes C, D, and E). Each additional millimeter of surface layer thickness leads to a 19% elevation of FE. The higher amount of wood particles and the resin used for increasing the surface layer thickness leads to the higher emission of formaldehyde (Petersen *et al.* 1972).

The use of surface layer separation techniques (*e.g.*, water spray or un-resinated particles) is one of the most important production stages in the one-step manufacturing process of foam core panels. Hence, to understand the effect of the separation techniques (water spray) on FE, the panel produced by the one-step process (code C) was compared with the reference panel (code F). The results showed that the FE from panels produced in a simulated one-step process had nearly doubled compared with those from the reference panels. The reason for this can be perceived in the sprayed water ( $60 \text{ g/m}^2$ ) used for surface layer separation. Petersen *et al.* (1972) have stated that the moisture content of the particleboard mat influenced the FE of the produced panels. For controlling the formaldehyde emission of the produced panels a solution of urea and water (code K) was applied for surface layer separation. A comparison of codes C and K showed that the addition of urea had halved (about 50%) the FE of the panels produced in a one-step manufacturing process. Urea is one of the most effective and at the same time cheapest formaldehyde scavengers available (Ashaari *et al.* 2016; Boran *et al.* 2011) in the market. The flask method is suitable only for internal production control of wood-based panels. Hence, no official limit values have been published.

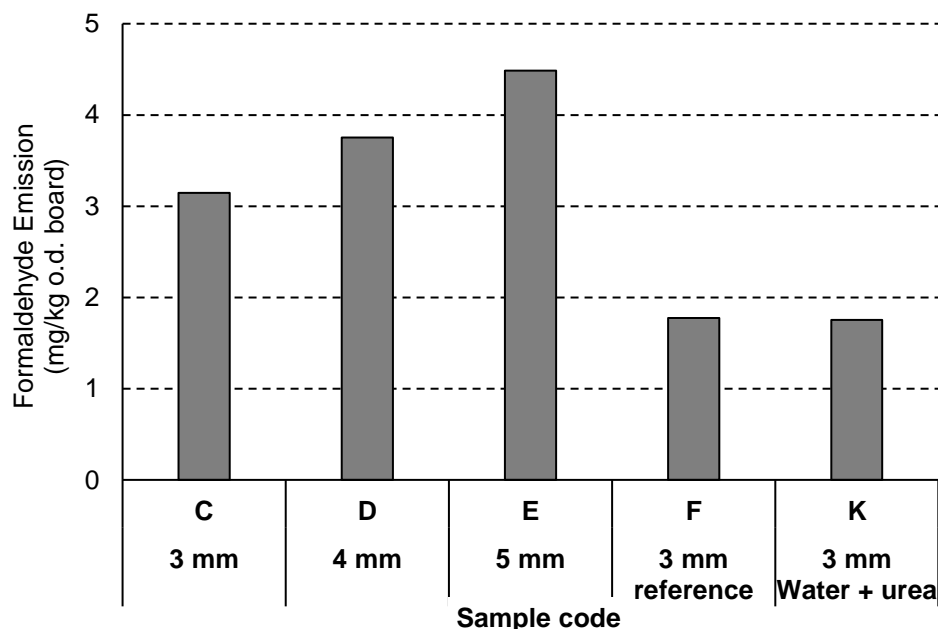


Fig. 10. Formaldehyde emission of foam core panels

## CONCLUSIONS

1. This study showed that foam core particleboards using rigid polyurethane as a core layer can be produced in a simulated one-step manufacturing process.
2. The research showed that the production techniques (separation and injection techniques) have no significant influence on the panel characteristics, but the panel properties of the reference panels and the ones produced by the simulated process were significantly different. The MOR, IB, and FSW values were significantly higher in reference panels because of their better surface layer quality.
3. Increasing the surface layer thickness (from 3 to 5 mm) enhances the MOR and FSW values and resulted in a significant decrease in IB. The TS and WA were also elevated by increasing the thickness of the surface layers.
4. The TS and WA were intensive during the initial soaking period (48 h) and afterwards slowed down. The results indicated that the surface layers were nearly saturated after the initial soaking time, which was reflected by the extremely low TS after the initial soaking time. However, water was still absorbed at the end of the soaking time (up to 786 h) because it migrates into the voids between the foam cells.
5. Increasing the surface layer thickness raises the FE from the samples. Sprayed water as a separation technique nearly doubles the FE from the samples, which can be controlled by adding urea to the sprayed water.
6. Generally speaking, the PU foam core particleboards showed good potential for use in furniture industries. Further research in polyurethane formulation will be needed to enhance the foam structure, which can accordingly affect the panel characteristics.

## ACKNOWLEDGMENTS

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