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Analysis of the relationship of quality factors in the solventless lamination process

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Abstract

The paper presents the necessity of establishing the priority ranking of factors which influence the solventless lamination process. The quality factors in the lamination process have been determined through the questionnaire survey of specialists experienced in the lamination of flexographic prints. To establish the priority of the quality factors in the flexographic prints lamination process, a ranking methodology was used which is based on the fact that the importance of the factor is determined by numerical indicators related to the number of influences and dependencies between the factors and their respective weight coefficients. The interconnections between the factors in the lamination process have been established and the model of the importance of quality factors in the solventless lamination process of flexographic prints was constructed with the help of the ranking method. In accordance with the obtained results, the following factors are of the highest priority: the construction of the section for adhesive supply, the type of adhesive, the complexity of the printed image, the type of material, web width, and the temperature. By the set terms, the fuzzy knowledge base of parameters in the solventless lamination process with the performance of the condition "if–then" has been formed. Based on this knowledge base, fuzzy logic equations for the calculation of the quality factors in the lamination process options have been built and defuzzification by the "center of gravity" method to get the quantitative quality parameters of the lamination technological process and to optimize the process.

Keywords: flexible packaging, factor analysis, process parameters, fuzzy logic

1. Introduction

The growing demands for strength, barrier properties and design of flexible packaging have stimulated the use of combined materials in its production, in particular from different types of polymer films, aluminium foil, paper and cardboard. This, in its turn, has given a new impetus to the development and improvement of laminating technologies – obtaining of complex multilayer materials through their combining (most often – gluing). Today, practically every printing company, specializing in the production of flexible packaging, has a laminator among its equipment. In the conditions of a large assortment of materials for lamination, adhesives and equipment, the requirements of finished laminates quality are also steadily increasing, so a comprehensive analysis of laminating technologies and the importance of criteria affecting the quality of the finished packaging is an urgent task.

2. Literature review

The segment of flexible packaging of the global packaging market demonstrates the highest pace of development. According to the forecasts by Smithers Pira (2015), an international analytical company, the average annual growth rate of the global flexible packaging market will remain at 3.4 % over the next five years, and by 2020 the market capacity will reach $ 248 billion. Such growth rates are supported by the demand for flexible packaging with huge potential for the developers of packaging technologies, polymer recyclers, and packaging manufacturers. Among the main trends in the development of the European market for flexible packaging in recent years, the following directions are clearly distinguished: the increase in the production of retort-packaging, the growth of production of materials with special and high barrier properties, the growth of the production of biodegradable polymers, the growth of the requirements for the quality of printing and the quality of packaging in general. All of these trends are directly related to the production of various types of laminates (Laminating, 2016).

Despite such a rapid development of packaging laminating technologies, printing experts did not pay sufficient attention to them. In particular, Lv, Xu and Zuo (2010) determined that the change of adhesive viscosity is the main factor of unevenness in coating thickness, in the work of Kyryliuk and Zorenko (2012) the main attention was paid to laminating technologies used in book and magazine production, in the production of postcards, etc. In the research paper of Izdebska, Żołek-Tryznowska and Wirtek (2015) it was found that the thickness of the ink, printed on the inside of the laminated film has a significant influence on the mechanical properties of the laminates. The paper from Havenko, et al. (2008) which describes a mathematical model of lamination strength and curling of laminates, depending on the paper properties, working speed and temperature, can serve as a useful basis for the research in this study.

With the technology of solventless lamination, a single- or two-component adhesive (most often on a polyurethane base) is applied on a material in a heated state. The unit for the adhesive application is a system of rollers, two of them are dosing; the adhesive is poured between them for the dosage. The transfer shaft transfers the adhesive to the working shaft from which it is applied to the web material. Manufacturers of equipment offer various construction solutions of this unit, which significantly influences the uniformity of the adhesive application (Wolf, 2010). It is technologically necessary to apply a minimum, but still sufficient layer of the adhesive in the amount of 1–4 g/m^2. After the adhesive application, two films that are passing through the system of pressing rollers are glued in the laminating unit. A separate unit is used as a mixing station of solventless two-component adhesive. Here both components – the resin and the hardener – are heated to a certain temperature and are fed through separate hoses to the mixing head, from which the ready-to-use adhesive enters the unit for its application. Most laminators are also equipped with an additional device for processing (activation) of films by corona discharge and a cooling cylinder (after the laminating unit).

The peculiarity of the technology of solventless lamination is that after gluing, the roll of the laminate should stand still for one or two days, before proceeding with the next technological operation in order to reach the final polymerization of the adhesive (this time is 3–6 hours with solvent lamination). Adhesives for solventless lamination have insufficient thermal stability, so the resulting laminates have limited resistance to sterilization.

On the other hand, the widespread application of the technology of solventless lamination has provided a number of advantages. In addition to its high performance, the undoubted advantage of this technology is its cost-effectiveness (Caimmi, et al., 2013). First, it is obvious that we save costs as there are no expenses for solvents. Secondly, the absence of drying devices can significantly save energy costs (up to 30 %). In addition, the solventless technology involves the application of very thin layers of adhesive without reducing the laminate quality. This technology is also more environmentally friendly since it does not use organic solvents.

The final quality of the finished packaging depends on the qualitative performance of the lamination process, and the control of the technological process is complicated by the fact that while the defect can be seen immediately during printing, the lamination defects appear with some delay – the material can exfoliate, wrinkle and telescope in a roll. Therefore, the question of controlling the quality of the solventless lamination process is important for all enterprises that use this technology.

3. Methods

3.1 Determining the importance of factors

To determine the factors that are important in the solventless lamination, a survey was conducted among eighteen experts (specialists in this technology). They expressed their opinion about the influence of various factors on the lamination process in the questionnaires. The questionnaires prepared according to the methodology by Gurgal, et al. (2013) were processed and twelve most important factors were identified. The importance of the factors with influence on the lamination process has been analyzed using the ranking method (Senkivsky and Pikh, 2013). The method of ranking is based on the fact that the importance of the factor is determined by numerical indicators concidering the number of influences and dependencies between factors and their respective weight coefficients.

Based on the survey of experts, an oriented graph is designed and the relationships between factors are determined. When analyzing the graph, we calculated the total weight value of direct and indirect influences of factors and their integral dependency on other factors. To do this, the following notation was introduced. Let k_{ij} to be the number of influences ($i = 1$ for direct, $i = 2$ for indirect) or dependencies ($i = 3$ for direct, $i = 4$ for indirect) for the j-th factor ($j = 1, ..., n$) and w_i to be the weight of the i-th type. For the calculations, the following conditional values for the weight coefficients in the conditional units were accepted: $w_1 = 10$, $w_2 = 5$, $w_3 = -10$, $w_4 = -5$.

The weight values of all types of relationships of quality factors were denoted by P_{ij}. To calculate it, the following equations were used:

$$P_{ij} = k_{ij}\, w_i \text{ for } i = 1, 2, 3, 4 \text{ and } j = 1, ..., n, \qquad [1]$$

where n – is the number of the factor.

For a designed oriented graph (Figure 1), taking into account Equation [1], we obtained:

$$P_{Fj} = \sum_{i=1}^{4}\sum_{j=1}^{m} k_{ij} w_i \qquad [2]$$

where m – is the number of factors determined in the questioning process.

If a factor is missing one of the types of relationships, the corresponding k_{ij} value in the Equation [2] is equal to zero. Thus, the given formula serves as the basis for obtaining weight values of the factor ranking, taking into account the different types of relationships between them. It should be noted that $P_{3j} < 0$ and $P_{4j} < 0$, since according to the given initial conditions $w_3 < 0$ and $w_4 < 0$. Consequently, in order to bring the total weight values of the factors to a positive value and using the property of division by 5, the Equation [2] is transformed into:

$$P_{Fj} = \frac{1}{5}\left(\sum_{i=1}^{4}\sum_{j=1}^{m} k_{ij} w_i + S_j\right), \qquad [3]$$

where

$$S_j = \max|P_{3j}| + \max|P_{4j}|. \qquad [4]$$

This technique has been successfully tested in the work of Repeta, Senkivsky and Piknevych (2014).

Qualitative parameters of solventless lamination process are the result depending on the characteristics of the used materials, equipment specifications and technological process modes, included in selected factors.

3.2 Factor analysis using fuzzy logic

One of the principles for analyzing and quantification of the factors that influence the quality of the process is the fuzzy logic through which it is possible to interpret ambiguous statements into the language of clear mathematical formulas and operate with fuzzy input data. Such principles are realized in the work of Bellman and Zadeh (1970), who laid the foundations of the direction of fuzzy logic and introduced the concept of some universal set for a certain problem area. The advantages of a systems with fuzzy logic are the ability to operate the fuzzy input data, for example, the values that continuously vary in time. The basics of fuzzy logic are applied to control web tension in roll-to-roll based printing systems (Ponniah, et al., 2012), for the model for calculation of numerical color reproduction quality value (Temponi, Fard, and Corley, 1999), for the method of calculating flexographic prints quality (Repeta and Kukura, 2016), etc.

In general, the evaluation of the laminated prints quality by means of fuzzy logic includes the following:

- the establishment of a universal term-set of values and its corresponding linguistic terms of the isolated quality factors (linguistic variables);
- the construction of matrices of pair wise comparisons for the set of linguistic terms for the corresponding interval of values of a universal set and obtaining the functions of membership for each matrix;
- the development of a fuzzy knowledge base using fuzzy logical statements such as "if–then";
- the construction of fuzzy logic equations based on the matrix of knowledge and the functions of membership, which determine the connection between the functions of membership of input and output data;
- the defuzzification of a fuzzy set, the essence of which is a calculation of the numerical indicator of the predicted quality, for example, by the method of the centre of gravity of a plane figure.

To simulate the influence of process factors on the quality of lamination and its evaluation by means of fuzzy logic, we used the possibilities of the development system of the fuzzy control system – the Fuzzy Logic Toolbox of the MATLAB computing environment. For the defuzzification operation, we used the principle of "the centre of gravity" (Rotshtein, Lariushkin and Mityushkin, 2008).

4. Results and Discussion

4.1 Determining the importance of factors

The following factors, which determine the quality of the solventless lamination process of flexographic prints, have been established in the survey:

k_1 – the viscosity of adhesive (VA);
k_2 – the lamination speed (SP);
k_3 – the type of adhesive (AD);
k_4 – the tension of the material tape (MT);
k_5 – the construction of the adhesive feeding section (CS);
k_6 – the width of the material (WM);
k_7 – the complexity of the printed sample (PP);
k_8 – the pressure in the contact area (PR);
k_9 – the surface properties of materials (SM);

k_{10} – the lamination temperature (LT);
k_{11} – the properties of the printing cylinder (PC);
k_{12} – the type of the material (TM).

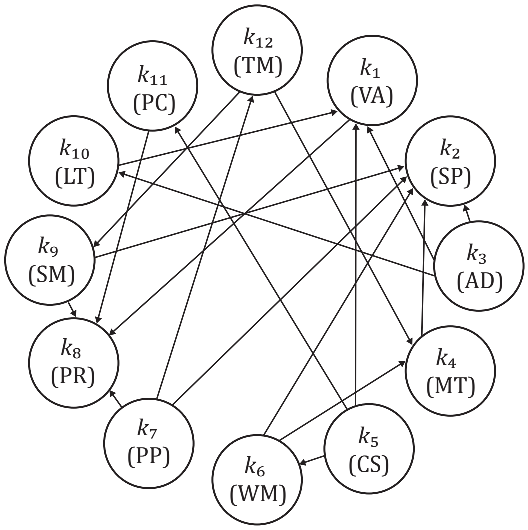

Figure 1: The graph of relationships between the factors

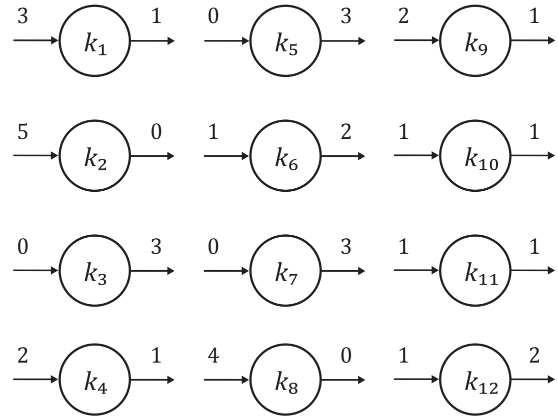

Figure 2: Influences and dependencies for quality factors of the solventless lamination process

The determined factors and possible relationships between them are presented in the form of an oriented graph (Figure 1). It indicates a certain interdependence of the individual factors of the solventless lamination process.

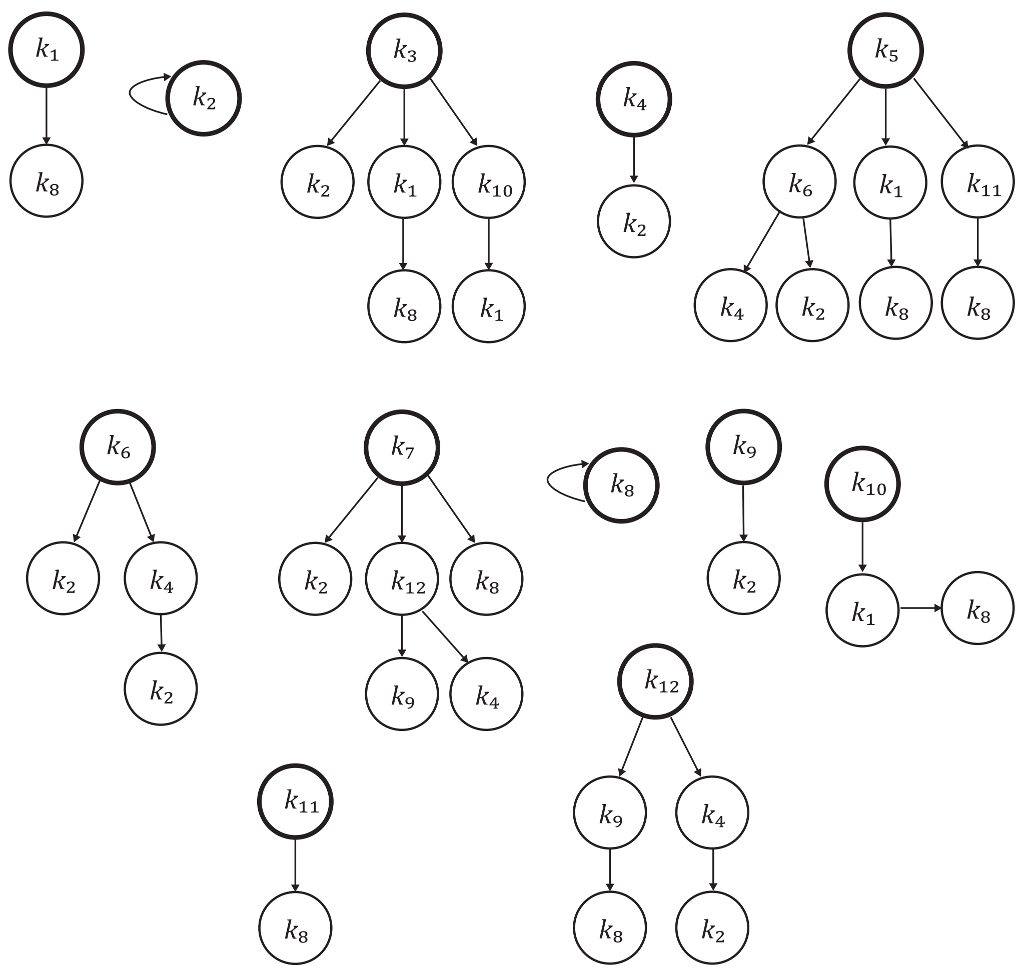

Figure 3: Graphs of multilevel hierarchical influences for quality factors of the solventless lamination process

Table 1: The calculated data of the factor ranking

Factor *j*	k_{1J}	k_{2J}	k_{3J}	k_{4J}	P_{1J}	P_{2J}	P_{3J}	P_{4J}	P_{FJ}	Level of ranking
k_1	1	0	3	1	10	0	−30	−5	9	10
k_2	0	0	5	3	0	0	−50	−15	1	12
k_3	3	2	0	0	30	10	0	0	22	2
k_4	1	0	2	2	10	0	−20	−10	10	9
k_5	3	3	0	0	30	15	0	0	23	1
k_6	2	1	1	0	20	5	−10	0	17	5
k_7	3	1	0	0	30	5	0	0	21	3
k_8	0	0	4	4	0	0	−40	−20	2	11
k_9	1	0	2	1	10	0	−20	−5	11	8
k_{10}	1	1	1	0	10	5	−10	0	15	6
k_{11}	1	0	1	0	10	0	−10	0	14	7
k_{12}	2	2	1	0	20	10	−10	0	18	4

To determine the number of factor influenced by given factor, we determined its direct influences, expressed by the corresponding coefficient k_{1j}. Similarly, coefficients k_{1j} were obtained to reflect the number of factors influencing given factor (Figure 2). The combined consideration of indirect influences or dependencies of the factor (i.e. the influence or dependency through other factors) reflect the coefficients k_{2j} and k_{4j}, respectively.

To do this, by analyzing an oriented graph (Figure 1), we constructed hierarchical trees of their relationships with other factors for each of the factors, taking into account the influences of both types – direct and indirect, which pass through another factor (Figure 3).

Based on the calculations, we formed Table 1 to determine the importance of factors. As we can see from the table, max$|P_{3j}|$ = 50; max$|P_{4j}|$ = 20, which we took into account when calculating in accordance with the above Equation [4]. Accordingly, the specified values were added in each of the rows to the sum of the values in the columns P_{1j}, P_{2j}, P_{3j} and P_{4j} and the result was divided by 5. Finally, we obtained the resulting weight of the factor, which serves as the basis for determining the rank (importance) of the factor r_j, which is equivalent to the priority of its influence on the lamination process. The best rank has the factor with the highest value P_{Fj}.

We designed a scheme of factors' priority based on the results of their importance for the lamination process (Figure 4).

In accordance with the results in Table 1, the most important factors are: k_5, k_3, k_7, k_{12}, k_6, and k_{10}.

The optimal selection and the observance of these factors will allow us to ensure the lamination process with the highest qualitative indicators. In particular, the observance and regulation of the temperature regime of the adhesive will stabilize its viscosity, the use of materials with narrower width will stabilize the tension of the web and enable to increase the speed of the lamination process, and on the other hand the sample with large saturated colour-printed areas can lead to the appearance of spots, due to decrease the surface free energy of the ink layer.

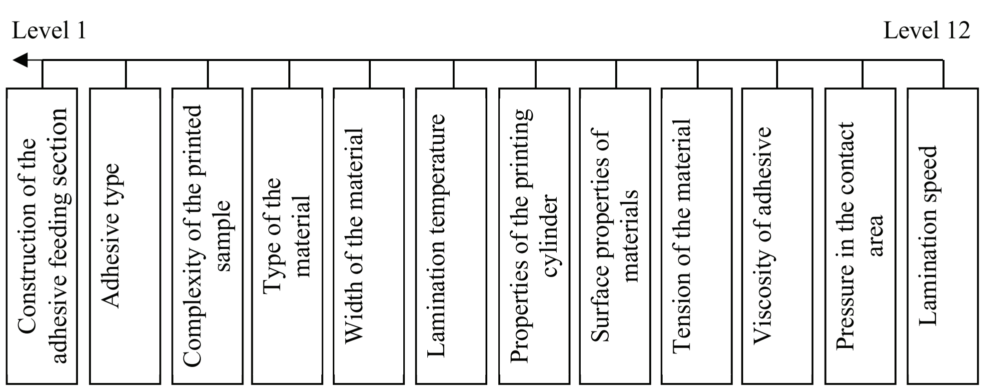

Figure 4: The model of the importance of quality factors of the solventless lamination process, as a result of the analysis of their relationships

4.2 Analysis of the process quality factors by fuzzy logic

The next stage of our work was an analysis of the technological process to determine the influence of the selected factors on the lamination quality. We assumed the following: the temperature regime of the process was stable; the settings of the machine were based on the type of material, which includes also its properties such as the film thickness and its "creep"; and the constructive invariability of the laminating machine was known. Then, for the next analysis, we took the indicators relating to the behavior of materials used in the process. Accordingly, the quality of the lamination process Q depends on the the the viscosity of the adhesive, the surface free energy of the polymer film, width of the film roll, and the speed of the material in the lamination process:

$$Q = f(V, E, W, S) \quad [5]$$

where V is a linguistic variable that characterizes the viscosity of adhesive; E is a linguistic variable that characterizes the value of the surface free energy of the film; W is a linguistic variable that characterizes the width of a laminated film; S is a linguistic variable that characterizes the speed of the lamination process. The evaluation of the values of linguistic variables has been carried out using the system of qualitative concepts. Each of these concepts is a corresponding fuzzy set, that is, some property that is considered as a linguistic term. For linguistic variables that provide the quality of lamination, Table 2 presents the calculated terms.

We continued from a fuzzy knowledge base for evaluating the parameter Quality of lamination using a set of fuzzy rules "if–then":

- If (Viscosity is 'Optimal') and (Surface free energy is 'High') and (Width is 'Narrow') and (Speed is 'High') then (Quality is 'High').
- If (Viscosity is 'Average') and (Surface free energy is 'High') and (Width is 'Wide') and (Speed is 'High') then (Quality is 'Low').
- If (Viscosity is 'Optimal') and (Surface free energy is 'High') and (Width is 'Wide') and (Speed is 'Medium') then (Quality is 'Medium').
- If (Viscosity is 'Optimal') and (Surface free energy is 'Low') and (Width is 'Wide') and (Speed is 'High') then (Quality is 'Low').
- If (Viscosity is 'High') and (Surface free energy is 'Satisfactory') and (Width is 'Narrow') and (Speed is 'High') then (Quality is 'Low').
- If (Viscosity is 'Optimal') and (Surface free energy is 'High') and (Width is 'Medium') and (Speed is 'Medium') then (Quality is 'High').
- If (Viscosity is 'Optimal') and (Surface free energy is 'High') and (Width is 'Narrow') and (Speed is 'Low') then (Quality is 'High').

We constructed the functions of membership for variable "Viscosity". The value of the indicator is defined on the universal set:
u_1 = 2 500 mPa·s; u_2 = 3 000 mPa·s; u_3 = 3 500 mPa·s; u_4 = 4 000 mPa·s; u_5 = 4 500 mPa·s; u_6 = 5 000 mPa·s; u_7 =5 500 mPa·s; u_8 = 6 000 mPa·s; u_9 = 7 000 mPa·s.
For a linguistic evaluation of this indicator, we used a set of fuzzy terms: T(V) = <Optimal, Average, High> (Figure 5a).

Similarly, we constructed the functions of membership for the variable "Surface free energy". The value of the indicator is defined on the universal set:
u_1 = 32 mJ/m^2; u_2 = 33 mJ/m^2; u_3 = 34 mJ/m^2; u_4 = 35 mJ/m^2; u_5 = 36 mJ/m^2; u_6 = 37 mJ/m^2; u_7 = 38 mJ/m^2; u_8 = 39 mJ/m^2; u_9 = 40 mJ/m^2.
For a linguistic evaluation of this indicator, we used a set of fuzzy terms: T(E) = <Low, Satisfactory, High>. Accordingly, we obtained the functions of membership of the linguistic variable "Surface free energy" (Figure 5b).

Table 2: The quality factors of the solventless lamination process

Variable name	Universal set	Level of ranking
Viscosity	2 500 to 7 000 mPa·s	Optimal Average High
Properties of materials (Surface free energy of polymer film)	32–40 mJ/m^2	Low Satisfactory High
Width of the material	30–100 cm	Narrow Medium Wide
Speed	100–180 m/min	Low Medium High

We obtained the functions of membership of the linguistic variable "Width" with fuzzy terms: T(W) = <Narrow, Medium, Wide>. The constructed functions of membership with corresponding terms for variables are shown in Figure 5c.

Accordingly, we defined the value for the indicator "Speed" on a universal set:
u_1 = 100 m/min; u_2 = 120 m/min; u_3 = 140 m/min;
u_4 = 160 m/min; u_5 = 180 m/min.
For a linguistic evaluation of this indicator, we used a set of fuzzy terms: T(S) = <Low, Medium, High>. And, similarly, we obtained the functions of membership of the linguistic variable "Speed" (Figure 5d).

The gradation of the linguistic variable "Quality of lamination" was determined in the following values: High – 10 conditional units; Low – 1 conditional unit.

The dependency of the initial parameter "Quality of lamination" on the values of the adhesive viscosity, the surface free energy, the width of the roll and the printing speed has been calculated on the basis of Mamdani and Assilian (1975) algorithm. The result of processing the introduced fuzzy rule, based on fuzzy inference system (FIS) editor, is shown in Figure 6.

The resulting model is based on the application of empirical knowledge obtained from the working expe-

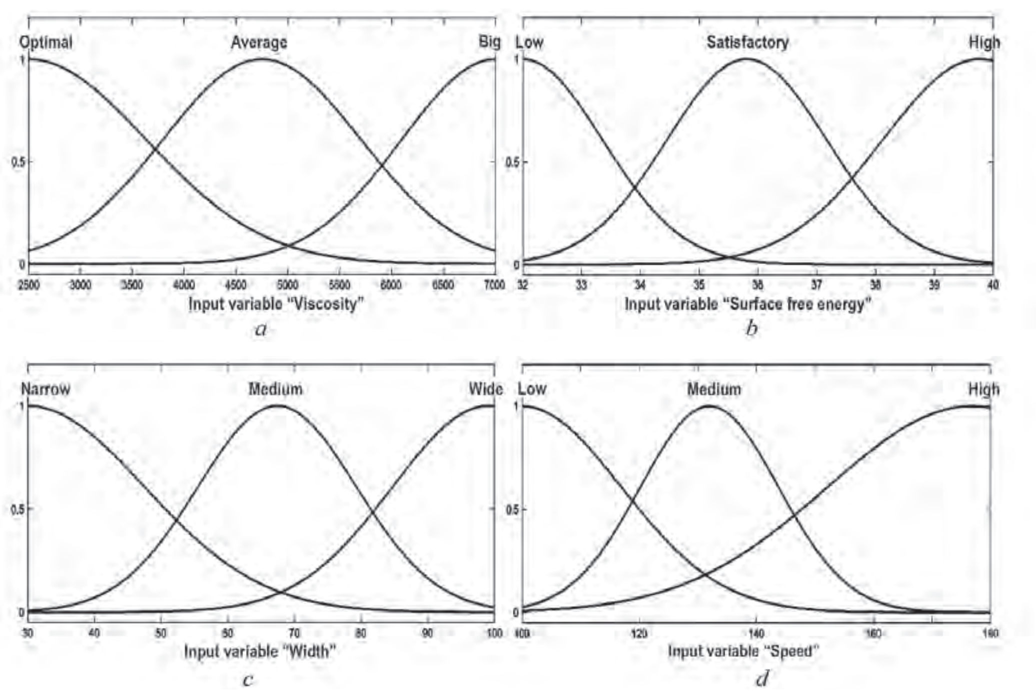

Figure 5: Functions of membership of the factors of solventless lamination: a – viscosity; b – surface free energy; c – width of the roll; d – speed

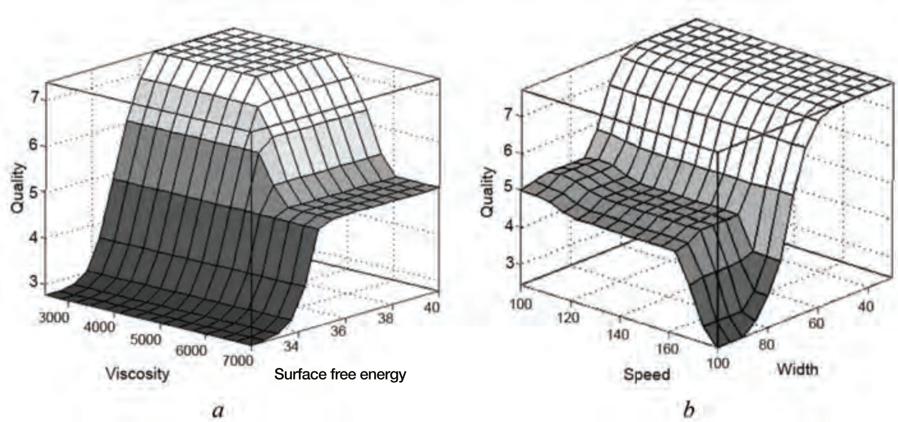

Figure 6: The model of the combined influence of factors on the quality of lamination process: a – the viscosity and the surface free energy; b – the speed and the width of the roll

rience and the observations of the technological process, and shows the influence of the selected factors on the quality of solventless lamination.

5. Conclusions

Thus, as a result of the analysis and the survey among experts, the factors of the quality of the lamination process have been determined, and due to the application of the ranking method, their importance in the solventless lamination process of flexographic prints has been calculated. The oriented graph and the synthesized model of the priority of the influence of factors have shown the dependency of some factors in relation to others. The analysis with the use of expert-linguistic information and the "if–then" rules has allowed us to obtain the functions of membership of such linguistic variables as the adhesive viscosity, the surface free energy of the films, the width of the roll and the speed of lamination, and to calculate their influence on the quality of the solventless lamination process. The suggested analysis of the process can be used to develop training systems, forecasting and control of the laminated prints quality of the solventless lamination process taking into account the remaining factors.

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